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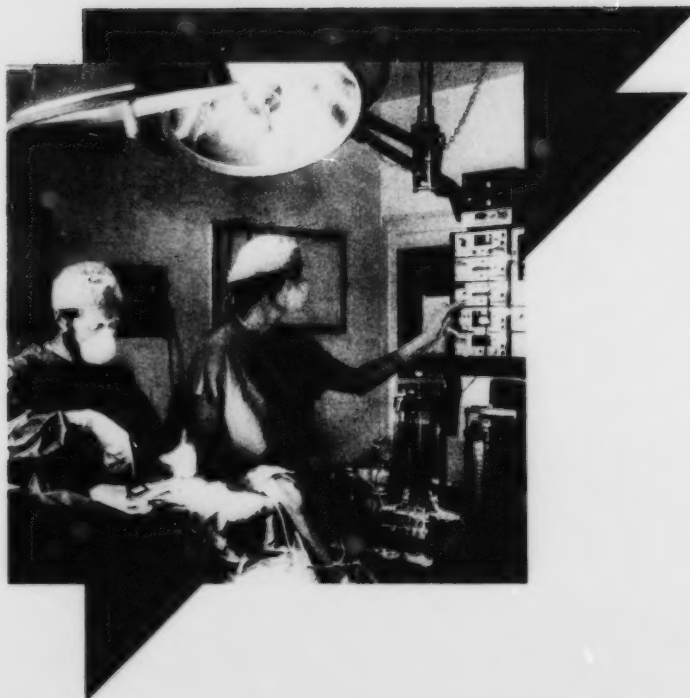
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Influence of Handrail Shape, Size and Surface Texture on the Ability of Young and Elderly Users to Generate Stabilizing Forces and Moments

B.E. Maki
August 1988



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INFLUENCE OF HANDRAIL SHAPE, SIZE AND SURFACE TEXTURE
ON THE ABILITY OF
YOUNG AND ELDERLY USERS TO GENERATE STABILIZING FORCES AND MOMENTS

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March 30, 1985

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J.L. Pauls, Scientific Authority

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TABLE OF CONTENTS

SUMMARY	vii
RÉSUMÉ	viii
ACKNOWLEDGEMENTS	x
 I Introduction	 1
 II Methodology	 4
2.1 Experimental Design	4
2.2 Apparatus	5
2.3 Subjects	11
2.4 Protocol	11
2.5 Analysis	15
 III Results - Handrail Shape and Size	 18
3.1 Force and Moment Generation	18
3.1.1 ANOVA for Handrail Shape and Size.....	18
3.1.2 Regression Analysis for Handrail Size	19
3.1.3 ANOVA for "Basic" and "Commercial" Handrails	19
3.2 Grip and Sliding Comfort Ratings	19
3.2.1 ANOVA for Handrail Shape and Size	19
3.2.2 ANOVA for "Basic" and "Commercial" Handrails	20
3.3 Avoidance	20
3.4 Slippage	20
3.5 Estimation of Optimal Design Values	21
3.6 Tables	22
3.7 Figures	27
 IV Results - Handrail Surface Texture	 43
4.1 Force and Moment Generation	43
4.2 Grip and Sliding Comfort Ratings	43
4.3 Avoidance	44
4.4 Slippage	44
4.5 Estimation of Optimal Design Values	44
4.6 Tables	45
4.7 Figures	48

V	Discussion of Results	64
5.1	Estimation of the Optimal Design Values	64
5.2	Unacceptable Design Values	65
5.3	Evaluation of the Experimental Surface Textures	65
5.4	Biomechanics	66
5.5	Interaction of Handrail Shape and Size	67
5.6	Limitations of the Present Study	67
5.6.1	Mounting Arrangements	67
5.6.2	Statistical Considerations	68
5.6.3	Limitations of Static Measurements	69
5.7	Figures	70
VI	Conclusions	73
	REFERENCES	74
	APPENDIX A - Details of the Surface Preparations	75

LIST OF FIGURES

1.1	Biomechanical Model of the Stairway User	3
2.1	"Basic" Handrail Shapes	6
2.2	"Commercial" Handrail Shapes	7
2.3	The Experimental Apparatus	8
2.4	Mounting Hardware: End Fixtures	9
2.5	Mounting Hardware: C-Clamps	10
3.1	Backward Moment versus Handrail Design - Data	27
3.2	Forward Moment versus Handrail Design - Data	28
3.3	Backward Force versus Handrail Design - Data	29
3.4	Forward Force versus Handrail Design - Data	30
3.5	Upward Force versus Handrail Design - Data	31
3.6	Backward Moment versus Handrail Design - Mean Values	32
3.7	Forward Moment versus Handrail Design - Mean Values	33
3.8	Backward Force versus Handrail Design - Mean Values	34
3.9	Forward Force versus Handrail Design - Mean Values	35
3.10	Upward Force versus Handrail Design - Mean Values	36
3.11	Grip Comfort versus Handrail Design	37
3.12	Slide Comfort versus Handrail Design	38
3.13	Avoidance Percentage versus Handrail Design	39
3.14	Slip Percentage versus Handrail Design	40
3.15	Grip Comfort - Percentage with Acceptable Ratings	41
3.16	Slide Comfort - Percentage with Acceptable Ratings	42
4.1	Backward Moment versus Handrail Surface - Data	48
4.2	Forward Moment versus Handrail Surface - Data	49
4.3	Backward Force versus Handrail Surface - Data	50
4.4	Forward Force versus Handrail Surface - Data	51
4.5	Upward Force versus Handrail Surface - Data	52
4.6	Backward Moment versus Handrail Surface - Mean Values	53
4.7	Forward Moment versus Handrail Surface - Mean Values	54
4.8	Backward Force versus Handrail Surface - Mean Values	55
4.9	Forward Force versus Handrail Surface - Mean Values	56
4.10	Upward Force versus Handrail Surface - Mean Values	57
4.11	Grip Comfort versus Handrail Surface	58
4.12	Slide Comfort versus Handrail Surface	59
4.13	Avoidance Percentage versus Handrail Surface	60
4.14	Slip Percentage versus Handrail Surface	61
4.15	Grip Comfort - Percentage with Acceptable Ratings	62
4.16	Slide Comfort - Percentage with Acceptable Ratings	63
5.1	Pinch Grip	70
5.2	Inadequate "Wrap-Around"	71
5.3	Finger "Interference"	72

LIST OF TABLES

2.1	Characteristics of the Subject Population	13
2.2	Details of Handrail Use during the Experiments.....	14
3.1	ANOVA of Force/Moment Generation for Handrail Shape and Size	22
3.2	ANOVA of Force/Moment Generation for Handrail Configuration	23
3.3	ANOVA of Comfort Ratings for Handrail Shape and Size	24
3.4	ANOVA of Comfort Ratings for Handrail Configuration	25
3.5	Summary of Design Estimates for Handrail Shape and Size.....	26
4.1	ANOVA of Force/Moment Generation for Handrail Surface	45
4.2	ANOVA of Comfort Ratings for Handrail Surface	46
4.3	Summary of Design Estimates for Handrail Surface	47

SUMMARY

The purpose of this study was to determine the influence of handrail shape, size and surface texture on stairway safety, for the purpose of improving building design standards. The present study is an extension of previous work, in which the influence of handrail height and stairway slope were investigated.

In preventing a stairway fall, the functional role of the handrail is to generate stabilizing forces and moments. The horizontal and vertical forces counteract undesirable forward and downward motion of the body. The moment generated about the metatarsophalangeal joints of the supporting foot counteracts the de-stabilizing moment due to body weight as well as the rotational momentum of the body.

The experiments involved measurement of the maximum stabilizing forces and moments that subjects were able to generate while standing stationary in an upright position. Changes in body position and orientation would be expected to change the forces and moments generated during an actual fall; however, static measurements of maximum voluntary effort (made in an erect posture) represent a reasonable approximation of the maximum stabilizing forces and moments that could be generated during the initial stage of a fall. It is felt that such measurements provide a basis for the comparison of handrail design.

The experiments also involved assessment of the preferences of the subjects with regard to gripping and sliding comfort, since it is possible that discomfort might discourage handrail use. In such a case, the probability of maintaining balance would be much reduced because of the time lag associated with the grabbing response.

Three basic shapes (circular, square and rectangular) were each tested in four sizes (circumferences ranging from 100 to 160 mm, or 4 to 6-1/2 inches). Four other commonly-used shapes were also tested. Eight different surface textures were tested. During the experiments, the subjects were restrained to control body position and to provide sufficient reaction forces on the body while pushing on the handrail. The handrail support was cantilevered and mounted to a force plate, so that the components of the applied force and moment in the sagittal plane could be measured. Measured forces and moments were normalized with respect to each subject's destabilizing body weight and associated moment, in order to quantify the potential stabilizing effect relative to corresponding destabilizing factors. Normalization allowed different subjects to be compared on a physically meaningful basis. Two age groups were tested: young (20 to 45) and elderly (60 and over), to examine possible age differences. Ten subjects (five males and five females), selected to represent a wide range of hand sizes, were tested for each age group.

Statistical analysis of the results showed that changes in handrail shape, size and surface texture did have some significant effects on the ability to generate stabilizing forces and moments and on the ratings of grip and sliding comfort. Overall, the circular shape and the two smaller sizes were found to be the best.

Based on the results, the recommended design is a circular shape with a circumference of 120 mm (diameter of 38 mm or 1-1/2 inches). The recommended surfaces are enamel, vinyl or glossy-varnish. "Narrow-top" rectangular and complex decorative shapes should be avoided, as should chrome, foam and roughened surfaces.

RÉSUMÉ

Le but de cette étude est de déterminer l'effet de la forme, des dimensions et de la texture des rampes sur la sécurité dans les escaliers afin d'améliorer les normes de conception des bâtiments. La présente étude fait suite à d'autres travaux visant à évaluer l'effet de la hauteur des rampes et de la pente des escaliers.

Dans la prévention des chutes dans les escaliers, la fonction de la rampe est de fournir des forces et des moments de stabilisation. Les forces horizontales et verticales doivent contrer les forces indésirables vers l'avant et vers le bas qui s'exercent sur le corps. Le moment produit au niveau des articulations métatarso-phalangiennes du pied d'appui contre le moment déstabilisant dû au poids et à l'élan rotatoire du corps.

Les expériences consistaient à mesurer les forces et moments de stabilisation maximaux que pouvaient produire les sujets debout en position stationnaire. Les variations dans la position et dans l'orientation du corps auraient sans doute un effet sur les forces et moments produits lors d'une chute réelle; toutefois, les mesures statiques de l'effort volontaire maximal (en position debout) permettent d'obtenir une approximation valable des forces et moments de stabilisation maximaux pouvant être générés aux premiers instants d'une chute. On croit que ce type de mesure fournit une base valable pour la comparaison de différentes hauteurs de rampe.

Les expériences incluaient également une évaluation des préférences des sujets relativement à la facilité de préhension et de glissement, car il est possible qu'un inconfort dissuade les personnes d'utiliser les rampes. Si c'était le cas, la capacité de garder son équilibre serait considérablement réduite en raison de la difficulté de s'agripper à la rampe.

Les essais ont porté sur trois formes de rampes (sections circulaire, carrée et rectangulaire) et sur quatre grosseurs pour chaque forme (circonférences de 100 à 160 mm ou largeurs de 4 à 6,5 pouces. Quatre autres formes couramment utilisées ont aussi été mises à l'essai. Au cours des expériences, les sujets devaient contrôler la position du corps et fournir les forces de réaction suffisantes en poussant sur la rampe. Le support de la rampe était monté en porte-à-faux et relié à un capteur de charges de façon que les composantes de la force et du moment appliqués dans le plan sagittal puissent être mesurées. Les forces et moments mesurés ont été pondérés en fonction du poids et du moment déstabilisant de chaque sujet afin de quantifier l'effet stabilisant potentiel contrant les facteurs déstabilisants correspondants. La pondération a permis de comparer des sujets différents sur des fondements physiques significatifs. Les essais ont porté sur deux groupes d'âge : les jeunes adultes (20 à 45 ans) et les personnes âgées (60 ans et plus) afin de connaître les écarts possibles selon l'âge du sujet. Dix sujets (cinq hommes et cinq femmes) choisis de manière à représenter une vaste plage de grandeurs de main ont subi l'essai dans chaque groupe d'âge.

L'analyse statistique des résultats a démontré que les variations dans la forme, les dimensions et la texture des rampes avaient un effet certain sur la capacité de produire les forces et moments stabilisants ainsi que sur les cotes subjectives de facilité de préhension et de glissement. Globalement, les rampes de section circulaire et des deux diamètres inférieurs ont été préférées.

D'après les résultats, la rampe recommandée est de section circulaire et de 120 mm de circonférence (diamètre de 38 mm ou 1,5 pouce). Les surfaces recommandées sont l'émail, le vinyle ou le vernis luisant. Les rampes de section rectangulaire à sommet étroit et les formes décoratives complexes sont à éviter, tout comme les surfaces chromées, en mousse ou rugueuses.

ACKNOWLEDGEMENTS

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In addition, I would like to thank the following companies for providing samples of handrails: ITT Fluid Products Canada (Guelph), Construction Specialties, Ltd. (Mississauga), and Alku Plastics, Ltd. (Downsview).

I would also like to thank the experimental subjects for their participation.

Brian Maki
March 30, 1985

I INTRODUCTION

Stairway falls are one of the most common causes of accidental injury (Templer, 1974). These falls are particularly serious in elderly stairway users because of their susceptibility to bone fracture (Brocklehurst, 1978). If properly designed, handrails should reduce the incidence of stairway falls; however, existing design standards have been derived with little regard to basic biomechanical principles (Maki and Fernie, 1983).

The overall objective of our work is to evaluate the effects of changes in handrail design on stairway safety, in order to develop more appropriate design standards. In previous studies (Maki and Fernie, 1983; Maki, 1984), we investigated the influence of handrail height on stairway safety at a single stairway slope of 33 degrees and at slopes of 41 and 49 degrees. The work described in this report is a study of handrail shape, size and surface texture.

Evaluation of the effectiveness of a given handrail design in preventing falls could involve: (1) in-the-field observation of stairway falls, or (2) laboratory studies using applied postural perturbations. The first approach is not practical, due to the low incidence at which falls normally occur and the lack of control over other variables (characteristics of the subjects, speed of gait, stairway traffic, etc). The second approach raises serious safety concerns. Even if a safety harness is used, the technique represents substantial risks for elderly subjects. Because of the difficulties inherent to the study of actual falls, an indirect method of assessment was developed, based on simple biomechanical principles.

In preventing a stairway fall, the functional role of the handrail is to generate stabilizing reaction forces and moments on the body. These forces and moments act on the body in reaction to the forces exerted by the hand on the handrail (see Figure 1.1). The horizontal and vertical forces counteract undesirable forward-backward and downward motion of the body. The stabilizing moment is also important. Modelling the initial stages of a fall as inverted-pendulum rotation about the metatarsophalangeal joints of the supporting foot, the moment generated by the handrail forces counteracts the rotational momentum of the body and the de-stabilizing moment due to body weight.

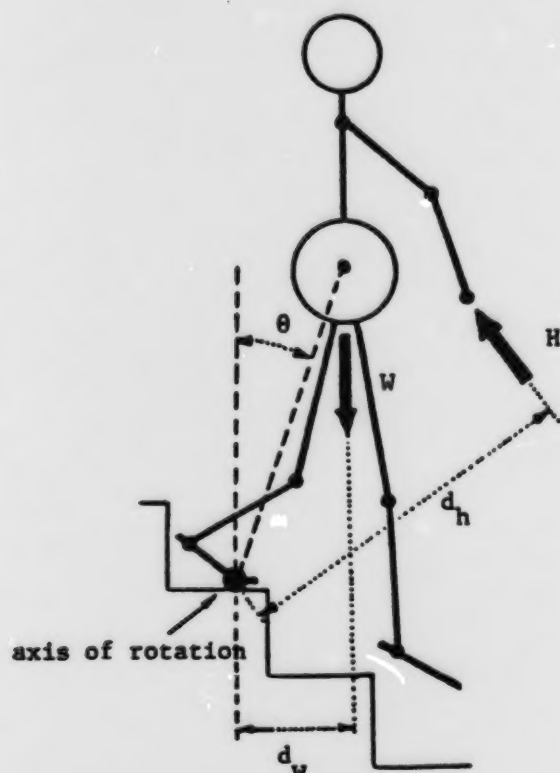
The experiments involve measurement of the maximum forces and moments that subjects are able to exert on handrails of various design, while standing stationary in an upright position. Increases in the generated moment and force are regarded as being indicative of an enhanced ability to counteract de-stabilizing moments and forces and to thereby recover from a loss of balance without falling.

The comfort of the subject is also assessed. If an individual feels uncomfortable using a particular handrail design, then he/she may avoid contacting the handrail while traversing the stairway. If a loss of

balance occurs, the individual must then grab for the handrail. Because of the time delay associated with the grabbing response, the probability of recovering balance without falling is much reduced in this situation. Thus, a good handrail design not only must allow the user to generate large stabilizing forces and moments, but must also be acceptably comfortable so that the user is not discouraged from maintaining handrail contact.

Ability to generate stabilizing handrail forces and moments is dependent on the location of the grip on the handrail and on the nature of the grip itself. Handrail height and stairway slope affect grip location but should have relatively little influence on the grip itself. Conversely, handrail shape and size will affect the type of grip, but should have little influence on the grip location. Surface texture is expected to affect ability to generate stabilizing forces and moments primarily through its influence on slippage of the hand, and should have little effect on the grip location or the nature of the grip.

This lack of interaction between certain design variables allows them to be studied in separate experiments. Thus, in our previous experiments, handrail height and slope were studied using a single handrail shape, size and surface texture. In the present experiment, handrail shape/size are studied using a single slope, height, and surface texture. Surface texture is studied using a single slope, height, size and shape.



Legend: θ = angle of inclination of inverted pendulum
 W = body weight; d_w = moment arm of body weight
 H = handrail force; d_h = moment arm of handrail force

Note: de-stabilizing torque = $W \times d_w$
 stabilizing torque due to handrail = $H \times d_h$

Figure 1.1 Biomechanical Model of the Stairway User

II METHODOLOGY

2.1 Experimental Design

The shape/size experiment was designed with two objectives in mind: (1) to allow general conclusions to be drawn regarding optimal handrail shape, size and the interaction between shape and size, and (2) to derive specific and practical design recommendations.

Towards the first objective, a number of basic shapes were each tested in a number of different size realizations. Three shapes were chosen: (1) circular, (2) square and (3) rectangular (width-to-thickness ratio = 3:1). For each shape, four different circumference sizes were tested, ranging from 100 mm to 160 mm. This range includes and extends beyond the range of sizes recommended by others (e.g. Armstrong, 1978). Note that the edges of the square and rectangular handrails were rounded, using a radius of 6 mm (1/4 inch), and that this effect is included in calculating the circumference of these handrails.

In addition to allowing a controlled study of size and shape, the results of these tests should also yield practical design recommendations, since these shapes can be fabricated easily in a number of materials. In fact, these shapes are already in wide usage and the specified range of sizes covers many existing handrail designs. In addition to these "basic" handrail designs, four other commonly-used handrail designs were tested. These designs were as follows: (1) oval, (2) "decorative", (3) rectangular "1x6" (width-to-thickness ratio = 5:28), and (4) rectangular "2x4" (width-to-thickness ratio = 4:9).

The various handrail designs tested in the experiments are shown full-size (with dimensions) in Figures 2.1 and 2.2. All of these test handrails were fabricated using the same surface texture: hardwood (birch or oak) finished with a matte-varnish.

In studying the influence of handrail surface texture, the test surfaces included several materials that are widely used and/or commercially available, as well as some materials that are not. The "commercial" surfaces included: (1) birch with a matte varnish finish, (2) birch with a glossy varnish finish, (3) chrome-plated steel, (4) enamelled steel, (5) vinyl, and (6) acrylic vinyl. (The vinyl had a smooth, glossy texture, whereas the acrylic vinyl had a dimpled texture). A birch handrail finished with a sand and paint mixture was tested to assess the feasibility of using roughened surfaces to minimize slippage. An aluminum tube covered with a sleeve (6 mm thick) of low-density polyurethane foam was tested, to assess the feasibility of using a compliant surface to enhance grip strength (particularly for elderly stairway users).

The details of the eight different surface preparations are given in Appendix A. These surfaces were all tested using the same handrail shape and size: a circular cross-section with a diameter of 44.5 mm (1-3/4 inch) (circumference of 140 mm). Note, however, that the acrylic vinyl handrail

was available only in a pre-fabricated form that included a flat metal surface (approximately 28 mm wide) on the underside of the handrail. Similarly, for the vinyl handrail, a 22-mm width of the underlying aluminum tubing was exposed on the underside of the handrail.

The shape/size and surface texture experiments were set up as randomized complete block designs. That is, all of the experimental subjects were tested with all of the handrails. The experimental methodology was similar to that used in the previous studies. A summary of the methodology appears below. For more details, consult the previous reports (Maki and Fernie, 1983; Maki, 1984).

2.2 Apparatus

The experimental apparatus, shown in Figure 2.3, included: (1) a mock stairway, (2) subject restraints, (3) 24 different test handrails, and (4) a force measurement system.

For these experiments, the slope of the mock stairway was set to 41 degrees. The mock stairway had standard tread and riser dimensions, i.e. a tread of 9 inches (229 mm) and a riser of 8 inches (203 mm), and an overhang (projected nosing) of 1 inch (25 mm) which is not included in the tread dimension listed above.

The mock stairway could be moved to allow the lateral displacement of the subject to be adjusted. Subjects were restrained posteriorly by a rigid, foam-cushioned back-board, and anteriorly by a canvas harness. The handrail was mounted on a rigid, cantilevered column, which was bolted to a piezoelectric force plate (Kistler, Model 9281). The slope and height of the handrail are adjustable, but were fixed for this experiment. The force plate was used to measure forces and bending moments in the sagittal plane. The output of the force plate was fed to charge amplifiers (Kiaag Swiss, Model 5001), and was then sampled at rate of 20 Hz, using an analog-to-digital converter unit (Neff, Model 920) and a minicomputer (Hewlett Packard, Model 9845). The sampled data were stored on magnetic disk for later analysis. The computer software plotted out the time records of the measured force and moment following each experimental trial so that the trial could be repeated if necessary.

Previous calibration of the experimental apparatus found a mean error of less than 10% and a correlation between applied and measured loads exceeding 0.997.

The test handrails (described in the previous section) were each approximately 1.27 m (50 inches) in length. They were supported in the test apparatus by means of "three-jaw chucks" located at each end. Cylindrical fittings (with a locating slot) were attached to the ends of each handrail, and these allowed the handrails to be inserted and removed from the chucks quickly and easily but with repeatable positioning and orientation. Two C-clamps were used to provide additional support when testing the two smallest rectangular handrails, so as to prevent excessive deflection under loading. The mounting hardware is shown in Figures 2.4 and 2.5.

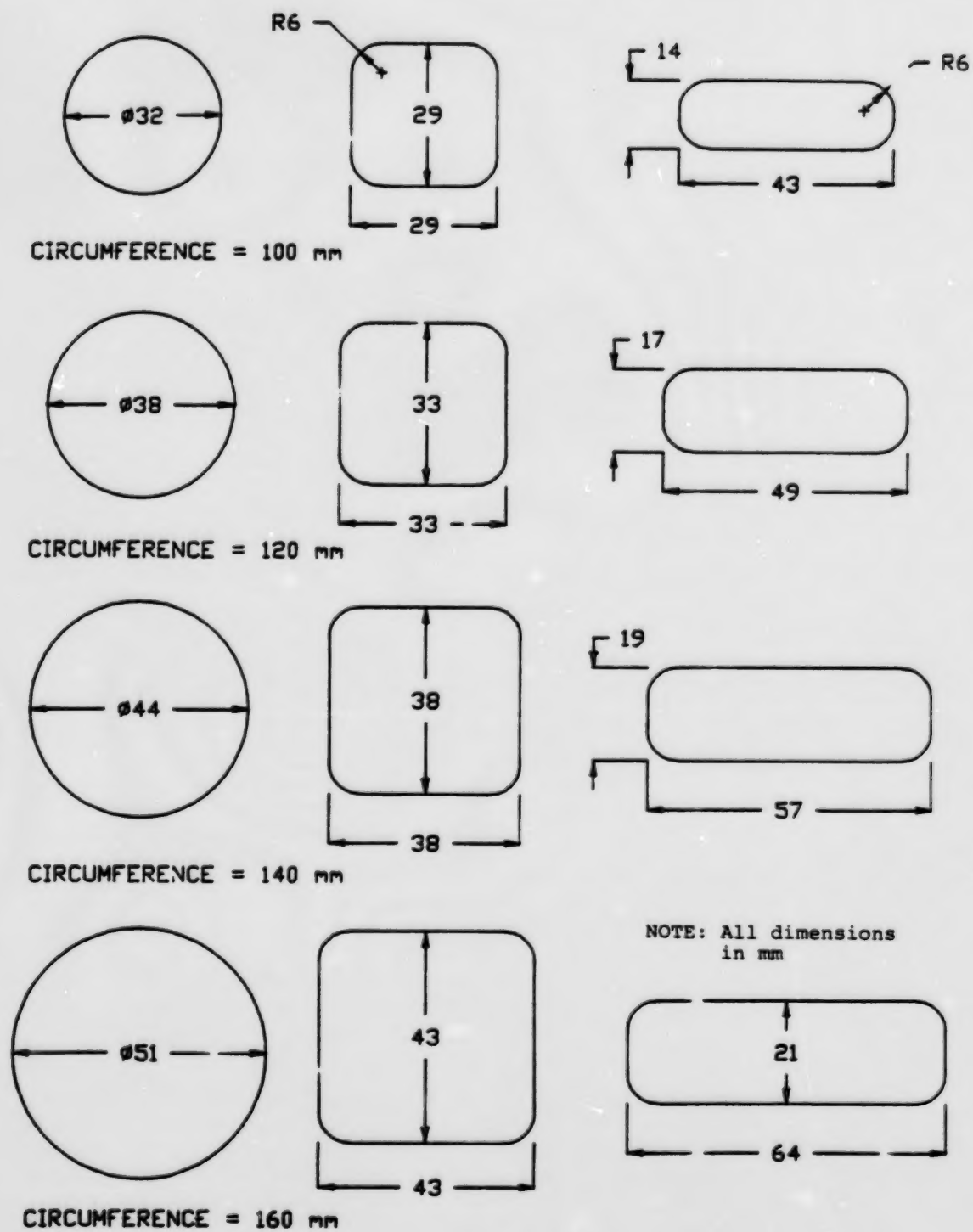
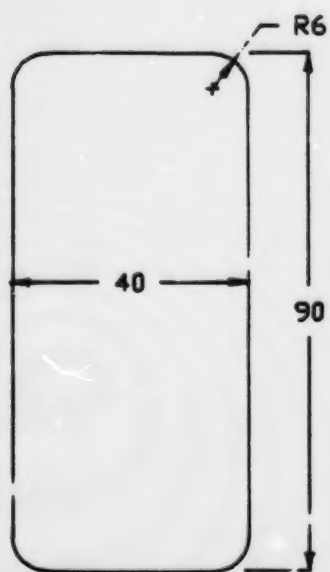
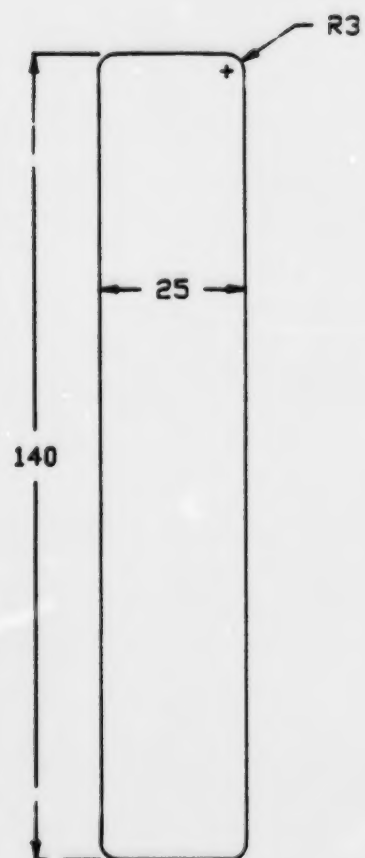


Figure 2.1 - "Basic" Handrail Shapes

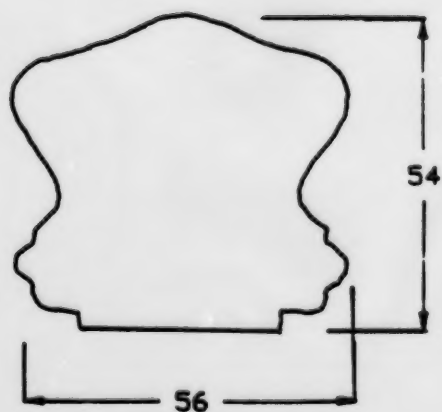


RECTANGULAR - '2x4'

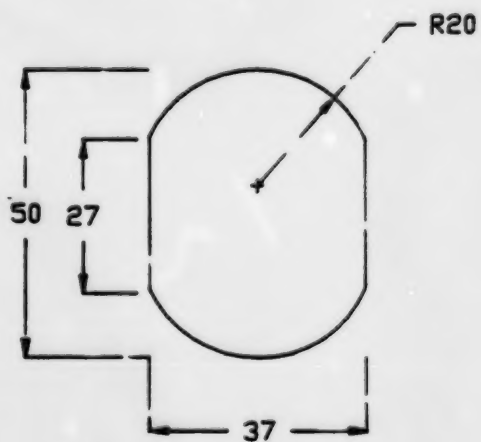
NOTE: All dimensions in mm



RECTANGULAR - '1x6'



'DECORATIVE'



OVAL

Figure 2.2 - "Commercial" Handrail Shapes

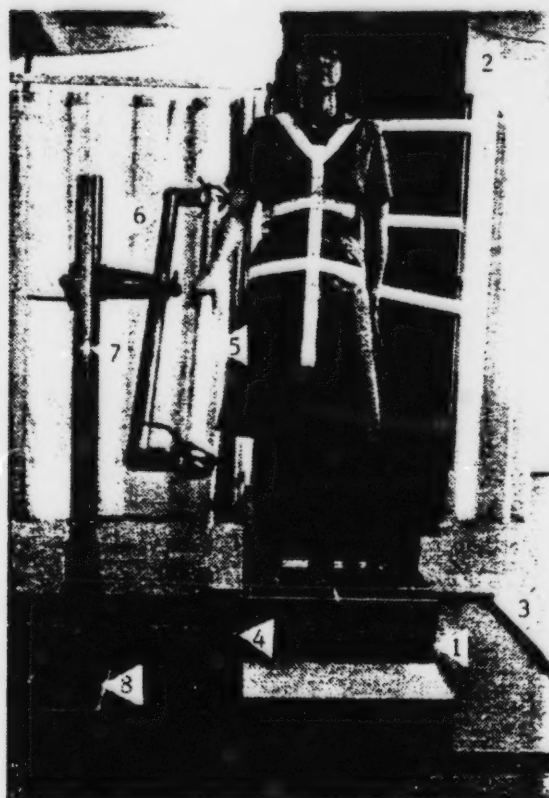


Figure 2.3 - The Experimental Apparatus

- Legend:
1. mock stairway
 2. restraining back-board
 3. tracks (for adjusting lateral displacement)
 4. scale for measuring lateral displacement
 5. handrail
 6. support for handrail
 7. scale for measuring height of handrail
 8. force plate

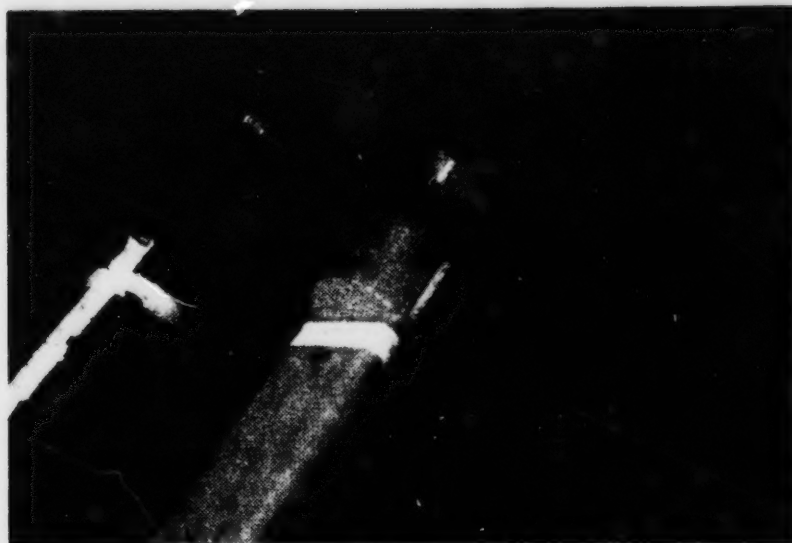


Figure 2.4 - Mounting Hardware: End Fixtures

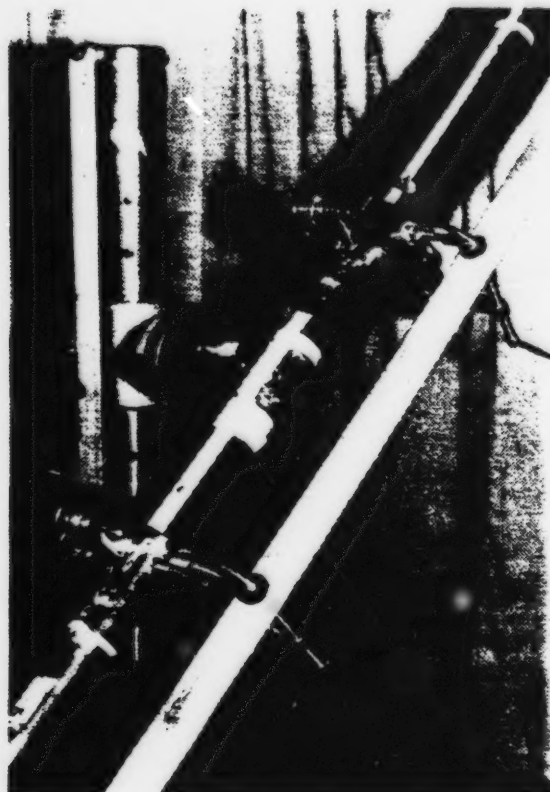


Figure 2.5 - Mounting Hardware: C-Clamps

2.3 Subjects

The study used only normal subjects, that is subjects with: (1) no evidence of significant neurological, vestibular, arthritic or musculoskeletal disorders or deficits, (2) no history of abnormal problems with dizziness or falling, and (3) no present regimen of drugs or medications that might affect neuromuscular function. Two age groups were studied: ten subjects were selected to be 60 or older, and ten subjects were selected between the ages of 20 and 45. There were equal numbers of males and females in each age group.

Because of the importance of hand size in gripping, the subjects were selected to provide a representative sample of the general population in terms of this characteristic. Using hand length data reported by Garrett (1971), treating males and females as separate populations, and assuming normal distributions for these populations, one subject of each sex was selected to represent each of the following ranges: (1) below the 20th percentile, (2) between the 20th and 40th percentile, (3) between the 40th and 60th percentile, (4) between the 60th and 80th percentile, and (5) exceeding the 80th percentile. All subjects were right-handed.

The non-elderly subjects were recruited from the staff and students at West Park Hospital and their friends. The elderly subjects were recruited from visitors and volunteers at the hospital, and from relatives and friends of hospital staff.

The characteristics of the subject population are shown in Table 2.1.

2.4 Protocol

Testing was performed in the stairway descent condition using a right-hand handrail. Handrail height and slope were held constant during the experiments. The handrail height was set at 930 mm (measured to the top surface of the handrail). This value corresponds approximately to the height recommended on the basis of the previous studies (i.e. 914 mm or 36 inches to the centre-line of a 44-mm diameter circular handrail). The handrail and stairway slope were set at 41 degrees, selected to represent the mid-range of existing stairway slopes.

Each subject was tested in two separate sessions. In the first session, the three "basic" shapes were each tested in the four different sizes. In the second session, the eight surfaces and four "commercial" shapes were tested. In each session, the order of testing was randomized. The initial test was used as a learning trial to allow the subjects to gain familiarity with the protocol, and was then immediately re-tested. The total testing time for each session varied from 45 to 90 minutes. Prior to the first experimental session, various body dimensions were measured.

At the beginning of the first session, each subject was instructed to select his/her preferred lateral displacement from the handrail and preferred grip location on the handrail by imagining that he/she was using the handrail while descending the mock stairway. These preferred values were used in all subsequent tests. The subject was then placed in the restraining harness and the distance from the metatarsophalangeal (MP) joints to the front of the tread was estimated. The preferred lateral displacement, MP joint-tread front distance, and grip location data are summarized in Table 2.2.

For each test handrail, the subjects were given two different instructions: (1) "push forward along the handrail" and (2) "pull backward along the handrail". Subjects were instructed to start exerting the force gradually, to increase up to their maximum ability and then to relax. If the rise-time to maximum force was less than 0.5 seconds or greater than 4.0 seconds, then the test was repeated. Audible tones at the beginning and end of the four-second period were used to guide the subject. In order to minimize inter-subject variation, all subjects were given the same standard set of instructions. In addition, to minimize motivational variation, spectators were not allowed, and no verbal encouragements were given by the experimenter. To minimize fatigue, subjects were allowed to move their feet and arms between force measurements and were given the option of taking a rest (sitting) midway through the session.

Note that in the two previous studies, four instructions were used; however, analysis of the results showed that the two instructions listed above invariably resulted in the largest forces and moments. By using only two instructions, the testing time was halved, thereby allowing twice as many handrail designs to be tested.

For each handrail, prior to the force/moment measurements, the subject was asked to rate the comfort of the handrail for gripping and for sliding the hand along. Rating was on a scale of one to five, as follows:

- 1 = very uncomfortable
- 2 = uncomfortable
- 3 = acceptable
- 4 = comfortable
- 5 = very comfortable

If the rating was unacceptable (less than 3), the subject was asked to give a reason and was then asked the following question: "Since you found this handrail uncomfortable, would you avoid holding onto it or sliding your hand along it while going down a stairway?". The response options to this question were:

- 1 = yes, regardless of how steep the stairway is
- 2 = yes, except for steep stairways
- 3 = no

Following each force/moment measurement, the subject was asked if he/she detected any slippage of the hand, and the experimenter observed the grip for possible problems, such as an inability to grip the undersurface of the handrail or interference between the fingertips and the palm.

TABLE 2.1 - CHARACTERISTICS OF THE SUBJECT POPULATION

	Mean +/- Standard Deviation		Range	
	Males	Females	Males	Females
<u>YOUNG SUBJECTS</u>				
Age (years)	33 +/- 6	27 +/- 6	26 - 40	21 - 36
Weight (kg)	78 +/- 6	57 +/- 5	73 - 85	51 - 63
Height (shod) (mm)	1820 +/- 75	1671 +/- 82	1746 - 1940	1580 - 1790
Armspan (mm)	1797 +/- 106	1673 +/- 61	1639 - 1934	1615 - 1773
Hand length (mm)	196 +/- 11	182 +/- 11	179 - 206	170 - 197
Grip circumference (mm)	124 +/- 10	116 +/- 9	112 - 135	100 - 125
Grip strength (kg)	44 +/- 12	30 +/- 3	26 - 60	28 - 35

ELDERLY SUBJECTS

Age (years)	70 +/- 6	67 +/- 5	60 - 76	61 - 74
Weight (kg)	75 +/- 8	61 +/- 7	65 - 84	52 - 68
Height (shod) (mm)	1777 +/- 37	1611 +/- 26	1741 - 1839	1589 - 1649
Armspan (mm)	1755 +/- 78	1568 +/- 46	1633 - 1841	1493 - 1615
Hand length (mm)	197 +/- 8	178 +/- 10	186 - 204	164 - 189
Grip circumference (mm)	126 +/- 7	106 +/- 9	116 - 133	94 - 118
Grip strength (kg)	34 +/- 6	19 +/- 4	28 - 44	12 - 22

NOTES:

- (1) armspan measured to tips of middle fingers (fingers extended);
- (2) hand length measured from wrist crease (base of semi-lunar bone) to tip of middle finger (extended);
- (3) grip circumference measured by sliding the hand down a cone so as to determine the maximum circular circumference that could be gripped when touching the tip of the thumb to the tip of the middle finger;
- (4) grip strength measured using a Smedley-type dynamometer, with spacing between handle surfaces set to 40 mm.

TABLE 2.2 - DETAILS OF HANDRAIL USE DURING THE EXPERIMENTS

	Mean +/- Standard Deviation		Range	
	Males	Females	Males	Females
<u>YOUNG SUBJECTS</u>				
Preferred lateral displacement (mm)	301 +/- 21	286 +/- 64	281 - 332	224 - 377
Location of metatarso-phalangeal joint (mm)	22 +/- 12	24 +/- 21	7 - 39	-4 - 52
Preferred grip location (mm)	13 +/- 47	55 +/- 68	-31 - 83	-56 - 109
<u>ELDERLY SUBJECTS</u>				
Preferred lateral displacement (mm)	301 +/- 42	308 +/- 61	244 - 335	244 - 390
Location of metatarso-phalangeal joint (mm)	2 +/- 23	11 +/- 7	-24 - 37	2 - 17
Preferred grip location (mm)	83 +/- 39	119 +/- 27	21 - 129	79 - 151

NOTES:

(1) lateral displacement is measured between the centre-line of the handrail and the centre-line of the body;

(2) location of the metatarsophalangeal joint is measured from the front of the riser to the estimated location of the metatarsophalangeal joint (i.e. the "ball" of the foot); a positive value indicates that the joint is behind the riser (in descending the stairway); a negative value indicates that the joint is in front of the riser;

(3) grip location is determined by locating the most anterior and most posterior points of the hand when gripping the handrail, and calculating the location of the middle of the grip as the mid-point between these two limits; the distance is measured along the handrail, from the plane of the anterior riser; a positive value indicates that the centre of the grip is anterior to this riser, a negative value indicates that it is posterior to this riser.

2.5 Analysis

The primary goals of the data analysis were as follows: (1) determine whether the ability to generate stabilizing forces and moments depends significantly on handrail shape, size and/or surface texture; (2) determine whether subjective perceptions of comfort depend significantly on handrail shape, size and/or surface texture; and (3) estimate optimal design values for handrail shape, size and surface texture, for use in building design.

The performance of each subject was characterized by the maximal force and moment that he/she was able to generate for each handrail design or surface. To show the relationship to the different types of falling motion, the components of the forces and moments (acting on the body) were analyzed separately, to yield the five variables listed below. Note that the variable names listed in brackets are used throughout the remainder of this report in referring to the five force and moment components. The five variables were:

1. maximum backward moment (Mb) (counteracts forward rotation)
2. maximum forward moment (Mf) (counteracts backward rotation)
3. maximum upward force (Fu) (counteracts downward translation)
4. maximum backward force (Fb) (counteracts forward translation)
5. maximum forward force (Ff) (counteracts backward translation)

The two moments (Mb and Mf) were calculated about an axis passing through the metatarsophalangeal joints of the feet. This axis was selected as an approximation of the axis of rotation of the body during the initial stages of a fall.

To eliminate intention tremor as well as other sources of noise, the raw data was passed through a twelfth-order, zero phase-lag digital low-pass filter, with cut-off at 1 Hz. Maximal values of the five stabilizing force and moment variables were found using the filtered data from the two experimental trials (i.e. two instructions) conducted at each handrail test condition.

Use of absolute force and moment values is meaningless in comparing different individuals, since the stabilizing effect of a given force or moment is dependent on the body weight and size of the individual. In order to compare different subjects, the force and moment variables were normalized with respect to body weight and body weight moment respectively. (Body weight moment is defined as the product of body weight and height of the centre-of-gravity and represents the maximum value of destabilizing moment due to body weight.) Each normalized value indicates the stabilizing effect of the handrail relative to the corresponding destabilizing factor (body weight or body weight moment) for a given individual. In all discussion that follows, normalization with respect to body parameters is assumed, unless specified otherwise.

Statistical analyses were performed on the normalized force and moment data and on the grip and sliding comfort ratings. In addition, the responses to the slippage and avoidance questions were tabulated. The slippage results were quantified as the percentage of subjects whose hand slipped while pushing or pulling on each handrail. The avoidance results were quantified as the percentage of subjects who would tend to avoid using each handrail.

For the analysis of handrail shape and size, the following analyses were performed: (1) two-way analysis of variance (ANOVA) with blocks was used to evaluate the effects of handrail size and shape on the generation of stabilizing forces and moments; (2) for each of the three "basic" shapes, a regression analysis was performed to examine the nature of the relationship between handrail size and ability to generate stabilizing forces and moments; and (3) two-way ANOVA with blocks was used to evaluate the effects of handrail size and shape on the grip and slide comfort ratings.

In addition, in order to compare the twelve "basic" handrails (3 shapes, 4 sizes) with the four "commercial" handrails, one-way ANOVA with blocks was used to analyze the force/moment data and the grip and slide comfort ratings.

For the analysis of handrail surface texture, one-way ANOVA with blocks was used to evaluate the effects of surface texture on generation of stabilizing forces and moments and on the grip and slide comfort ratings.

In all of the analyses, the two age groups were treated separately, since the previous studies have already demonstrated that highly significant age differences do exist (preliminary analysis confirmed these age differences in the present data). In the ANOVA analyses of force/moment generation and grip and sliding comfort ratings, the subjects were treated as blocks. To allow use of the ANOVA methods, the comfort ratings were approximated as being continuous normal variables.

In cases where the ANOVA showed significant differences between the mean forces/moments or comfort ratings for the different handrails, Tukey pairwise comparisons were used to rank the different handrails from highest to lowest. In this analysis, pairs of mean values were analyzed for significant differences. Mean values that showed no significant difference were ranked together as a group. Once a grouping was established, other values were ranked by comparison with the highest value in the group.

In order to estimate the optimal design values, it is necessary to consider the distribution of the generated forces and moments for the user population. The best handrail design will allow the largest percentage of the user population to generate the largest forces and moments. Assuming normality, each distribution is characterized by its mean and standard deviation. Performance of the user population in using the different handrail designs can be compared by selecting some arbitrary percentile

value on the distribution. One such percentile value can be calculated by subtracting one standard deviation from the mean. This value is the 17th-percentile, that is, it represents the normalized force or moment which 83% of the population would exceed in using that particular handrail. The best handrail designs will have the highest values for the 17th-percentile.

The sample mean and standard deviation values (calculated from the experimental data) are only estimates for the true mean and standard deviation of the user population, and hence yield only estimates for the true 17th-percentile values. While it may be possible to compare the 17th-percentile estimates by means of non-parametric statistical tests, this type of analysis is beyond the scope of the present investigation. Instead, the estimates of the 17th-percentile for the different handrail designs were examined for differences that were felt to be sufficiently large so as to have some physical significance.

For the young subjects, differences of less than 0.025 in normalized force or moment were regarded as having little physical significance. Such a difference would correspond to a force of approximately 1-kg for a 50-kg individual. Changes of this magnitude in the generated force or moment would probably have little effect in preventing a fall. For the elderly subjects, the corresponding value was selected as 0.0125. Since the elderly generate only half the force/moment magnitudes achieved by young adults, 0.0125 and 0.025 represent approximately the same percentage of maximum force/moment generating ability for the respective age groups. Furthermore, because of the slower gait of the elderly, a smaller change in force/moment may have a larger stabilizing effect, compared to young adults.

The "acceptable" handrail designs were defined as those with 17th-percentile forces or moments within 0.025 (for the young subjects) or 0.0125 (for the elderly subjects) of the highest 17th-percentile value recorded. Analysis of each of the five force and moment variables yielded a number of handrail shapes, sizes and surface textures that were deemed to be acceptable based on this criterion. Overall, the optimal handrail designs were chosen as those that: (1) were deemed to be acceptable on the basis of all five force/moment analyses, (2) were acceptably comfortable for at least 70% of the subject population (for both gripping and sliding), and (3) would not be avoided by more than 30% of the subject population.

III RESULTS - HANDRAIL SHAPE AND SIZE

3.1 Force and Moment Generation

The normalized force and moment data for the various handrail shapes and sizes are plotted in Figures 3.1 to 3.5. Each plot represents the variation of a given normalized force or moment as a function of the handrail design. The result for each subject is plotted as a line to allow trends to be identified. Results for the young and the elderly subjects have been plotted on separate graphs.

The mean normalized force and moment values (and corresponding standard deviations) are shown in Figures 3.6 to 3.10. These plots represent the distribution of force/moment generating ability occurring within each age group as a function of handrail design.

3.1.1 ANOVA for Handrail Shape and Size

The results of the analysis of variance are summarized in Table 3.1. The mean force/moment values are shown for the three shapes and four sizes, as are the rankings of these mean values (based on differences significant at $p=0.05$). Note that each age group was analyzed separately and that each of the five normalized force and moment variables was analyzed separately.

The ANOVA showed significant interaction (at $p=0.05$) between handrail shape and size in only one case, backward moment for the young subject group. This interaction implies that the best backward moment generation was achieved using a particular combination of handrail shape and size, and that the shape and size cannot be analyzed separately, for this particular variable.

For the young subjects, there were significant differences ($p=0.05$) between the different handrail shapes for variables M_f , F_b and F_u . For F_b , the circular and square shapes allowed the largest forces and moments to be generated. For M_f , the circular and rectangular shapes ranked first. For F_u , the circular shape was significantly better than the others. For the elderly subjects, there were no significant differences between the handrail shapes, for any of the five force/moment variables.

There were significant differences ($p=0.05$) between the different handrail sizes in generating backward force (both age groups) and backward moment (elderly subjects only). For the young subjects, the 140-mm size resulted in the lowest backward forces. For the elderly subjects, the 160-mm size was significantly poorer than the others.

Overall, the results imply that the circular shape is likely to result in the generation of the largest stabilizing forces and moments for a stairway user population including young adults. For a user population including young and elderly adults, the two smaller circumferences (100-mm and 120-mm) are the best sizes.

3.1.2 Regression Analysis for Handrail Size

For each of the three shapes, the nature of the relationship between the force/moment values and handrail size was evaluated using linear regression analysis. The results of this analysis show no strong relationship between force/moment generation and handrail size, as evidenced by very low values of correlation coefficient. This was found to be true even when higher order terms (quadratic and cubic) were included in the regression model.

3.1.3 ANOVA for "Basic" and "Commercial" Handrail Configurations

The results of the analysis of variance are summarized in Table 3.2. In this analysis, the twelve "basic" handrail configurations were compared with the four "commercial" configurations. As before, each age group was analyzed separately and each of the five normalized force and moment variables was analyzed separately. In the table, the mean force/moment values are shown along with the ranking (based on differences significant at $p=0.05$) for the 16 different handrails.

With one exception (F_u for the young subjects), the results showed some significant differences ($p=0.01$) between the mean forces and moments generated using the different handrail configurations. There were no significant differences between the mean values for the twelve "basic" handrails and the oval handrail. In general, the "decorative", "rectangular-2x4", and "rectangular-1x6" handrails were significantly poorer than the other handrails.

3.2 Grip and Sliding Comfort Ratings

The mean grip comfort and sliding comfort ratings (and associated standard deviations) are shown in Figures 3.11 and 3.12. These values, plotted as a function of handrail design, represent the distribution of comfort preferences of the two age groups.

3.2.1 ANOVA for Handrail Shape and Size

The results of the analysis of variance of the comfort ratings are summarized in Table 3.3. Each age group was analyzed separately and the two comfort ratings were analyzed separately. For each of the three shapes and four sizes, the mean ratings and rankings (based on differences significant at $p=0.05$) are shown.

The analysis showed significant interaction ($p=0.05$) between handrail shape and size for the elderly subjects. This result implies that certain combinations of size and shape may produce the best force/moment generation and that the optimal size and shape cannot be determined independently of each other.

For the young subjects, there were significant differences ($p=0.01$) between the comfort ratings of the different handrail shapes, for both grip and sliding comfort. The circular shape was rated significantly higher than the square or rectangular shapes. There were no significant differences between the handrail sizes.

3.2.2 ANOVA for "Basic" and "Commercial" Handrail Configurations

The results of the analysis of variance of the comfort ratings are summarized in Table 3.4. In this analysis, the twelve "basic" handrail configurations were compared with the four "commercial" configurations. As before, each age group was analyzed separately and the two comfort ratings were analyzed separately. In the table, the mean comfort ratings values are shown along with the ranking of these values (based on differences significant at $p=0.05$).

There were some significant differences ($p=0.01$) between the comfort ratings of the different handrail configurations. In general, the circular (all four sizes) and the oval handrails had the highest ratings. For grip comfort, the "decorative", "rectangular-2x4", and "rectangular-1x6" configurations were generally rated significantly poorer than the other handrails.

3.3 Avoidance

In Figure 3.13, the percentage of subjects who stated that they would avoid holding or sliding their hand along a particular handrail is plotted as a function of handrail design. These values include those subjects who stated that they would avoid the handrail in any circumstance as well as those who stated that they would avoid the handrail except on steep stairways.

It is evident from the plots that few subjects would avoid the circular, square or oval handrails. The same is true for the smaller rectangular handrails. However, a sizeable portion would tend to avoid the larger rectangular handrails and an even larger portion would tend to avoid the decorative, "rectangular-1x6" and "rectangular-2x4" handrails.

3.4 Slippage

The percentage of subjects who detected slipping of their hands while pushing or pulling on the handrail is plotted as a function of handrail design in Figure 3.14. While there was some incidence of slippage for all of the handrails, the "decorative", "rectangular-1x6" and "rectangular-2x4" handrails clearly showed the highest incidence of slippage.

3.5 Estimation of Optimal Design Values

In Figures 3.6 to 3.10, the lower end of each data bar represents the estimate for the 17th-percentile moment or force. Table 3.5 lists the handrail designs that are deemed to be acceptable, based on the values for the 17th-percentile forces and moment. The criterion for selection is described in Section 2.5. The table also lists those designs deemed to be acceptable on the basis of grip comfort, sliding comfort and avoidance, using the criteria of acceptability discussed in Section 2.5. (In connection with this analysis, Figures 3.15 and 3.16 show the percentage of subjects who rated each handrail "acceptable" or better.)

Overall, the recommended designs are those which were found to be acceptable on the basis of force/moment generation (for all five forces and moments) and on the basis of comfort (grip, slip and avoidance). For the young subjects, the recommended designs are "oval" and "circular-120 mm". For the elderly subjects, the recommended surfaces are "circular-120 mm", "circular-140 mm", and "square-100 mm". Including both age groups, the optimal design would seem to be the circular cross-section with circumference of 120 mm.

TABLE 3.1 - ANOVA of Force/Moment Generation for Handrail Shape and Size

	Mb Backward Moment	Mf Forward Moment	Fb Backward Force	Ff Forward Force	Fu Upward Force
<u>YOUNG SUBJECTS</u>					
F-values:					
shape	4.52 *	6.91 **	3.35 *	0.65	7.71 **
size	2.91 *	1.73	2.76 *	0.14	1.24
interaction	2.25 *	0.79	1.85	0.08	1.62
Shape means (ranking):					
circular	0.193 (I)	0.218 (1)	0.184 (1)	0.207 (NS)	0.353 (1)
square	0.182 (I)	0.196 (2)	0.174 (1)	0.187 (NS)	0.320 (2)
rectangular	0.178 (I)	0.212 (1)	0.172 (2)	0.198 (NS)	0.306 (2)
Size means (ranking):					
100 mm	0.189 (I)	0.218 (NS)	0.182 (1)	0.203 (NS)	0.317 (NS)
120 mm	0.192 (I)	0.203 (NS)	0.183 (1)	0.191 (NS)	0.332 (NS)
140 mm	0.177 (I)	0.211 (NS)	0.169 (2)	0.200 (NS)	0.326 (NS)
160 mm	0.178 (I)	0.205 (NS)	0.172 (1)	0.195 (NS)	0.338 (NS)
<u>ELDERLY SUBJECTS</u>					
F-values:					
shape	1.17	1.90	0.55	2.34	1.90
size	8.87 **	0.11	10.2 **	0.06	0.95
interaction	1.92	0.37	1.91	0.19	1.08
Shape means (ranking):					
circular	0.124 (NS)	0.133 (NS)	0.109 (NS)	0.118 (NS)	0.211 (NS)
square	0.126 (NS)	0.127 (NS)	0.110 (NS)	0.113 (NS)	0.211 (NS)
rectangular	0.121 (NS)	0.129 (NS)	0.107 (NS)	0.113 (NS)	0.202 (NS)
Size means (ranking):					
100 mm	0.130 (1)	0.129 (NS)	0.117 (1)	0.114 (NS)	0.202 (NS)
120 mm	0.129 (1)	0.131 (NS)	0.113 (1)	0.115 (NS)	0.211 (NS)
140 mm	0.122 (1)	0.129 (NS)	0.108 (1)	0.114 (NS)	0.208 (NS)
160 mm	0.113 (2)	0.129 (NS)	0.098 (2)	0.115 (NS)	0.210 (NS)

NOTE:

* indicates significant difference between means at p=0.05

** indicates significant difference between means at p=0.01

NS indicates no significant difference between means

I indicates that means cannot be ranked, due to interaction

TABLE 3.2 - ANOVA of Force/Moment Generation for Handrail Configuration

		Backward Moment	Forward Moment	Backward Force	Forward Force	Upward Force
<u>YOUNG SUBJECTS</u>						
F-values:		8.89 **	9.60 **	9.43 **	6.00 **	1.44
Mean values (ranking):						
circular	100	0.189 (1)	0.226 (1)	0.181 (1)	0.210 (1)	0.338 (NS)
	120	0.191 (1)	0.209 (1)	0.182 (1)	0.197 (1)	0.338 (NS)
	140	0.196 (1)	0.218 (1)	0.185 (1)	0.207 (1)	0.353 (NS)
	160	0.198 (1)	0.223 (1)	0.189 (1)	0.213 (1)	0.371 (NS)
square	100	0.200 (1)	0.214 (1)	0.190 (1)	0.201 (1)	0.320 (NS)
	120	0.192 (1)	0.188 (1)	0.183 (1)	0.177 (1)	0.313 (NS)
	140	0.167 (1)	0.196 (1)	0.159 (1)	0.188 (1)	0.320 (NS)
	160	0.167 (1)	0.190 (1)	0.161 (1)	0.182 (1)	0.310 (NS)
rectangular	100	0.179 (1)	0.213 (1)	0.174 (1)	0.198 (1)	0.294 (NS)
	120	0.193 (1)	0.213 (1)	0.184 (1)	0.199 (1)	0.346 (NS)
	140	0.169 (1)	0.219 (1)	0.163 (1)	0.204 (1)	0.306 (NS)
	160	0.171 (1)	0.203 (1)	0.166 (1)	0.191 (1)	0.332 (NS)
oval		0.186 (1)	0.210 (1)	0.177 (1)	0.201 (1)	0.317 (NS)
decorative		0.150 (2)	0.169 (2)	0.143 (2)	0.164 (2)	0.270 (NS)
rect-1x6		0.116 (2)	0.146 (2)	0.105 (2)	0.146 (2)	0.274 (NS)
rect-2x4		0.119 (2)	0.148 (2)	0.111 (2)	0.146 (2)	0.271 (NS)
<u>ELDERLY SUBJECTS</u>						
F-values:		10.73 **	8.74 **	10.78 **	5.93 **	2.26 **
Mean values (ranking):						
circular	100	0.129 (1)	0.134 (1)	0.115 (1)	0.118 (1)	0.198 (1)
	120	0.128 (1)	0.135 (1)	0.113 (1)	0.120 (1)	0.213 (1)
	140	0.125 (1)	0.132 (1)	0.109 (1)	0.117 (1)	0.217 (1)
	160	0.114 (1)	0.131 (1)	0.100 (1)	0.118 (1)	0.214 (1)
square	100	0.133 (1)	0.127 (1)	0.118 (1)	0.113 (1)	0.211 (1)
	120	0.133 (1)	0.129 (1)	0.117 (1)	0.113 (1)	0.218 (1)
	140	0.130 (1)	0.128 (1)	0.114 (1)	0.114 (1)	0.210 (1)
	160	0.106 (1)	0.124 (1)	0.091 (2)	0.111 (1)	0.204 (1)
rectangular	100	0.129 (1)	0.127 (1)	0.116 (1)	0.112 (1)	0.197 (1)
	120	0.125 (1)	0.128 (1)	0.109 (1)	0.113 (1)	0.202 (1)
	140	0.112 (1)	0.127 (1)	0.100 (1)	0.112 (1)	0.197 (1)
	160	0.118 (1)	0.133 (1)	0.104 (1)	0.116 (1)	0.213 (1)
oval		0.113 (1)	0.116 (1)	0.097 (1)	0.104 (1)	0.203 (1)
decorative		0.098 (2)	0.102 (2)	0.083 (2)	0.093 (2)	0.197 (1)
rect-1x6		0.067 (2)	0.086 (2)	0.055 (2)	0.081 (2)	0.171 (2)
rect-2x4		0.084 (2)	0.094 (2)	0.070 (2)	0.087 (2)	0.201 (1)

NOTE: * indicates significant difference between means at $p=0.05$ ** indicates significant difference between means at $p=0.01$

NS indicates no significant difference between means

TABLE 3.3 - ANOVA of Comfort Ratings for Handrail Shape and Size

	Grip Comfort	Sliding Comfort
<u>YOUNG SUBJECTS</u>		
F-values:		
shape	44.9 **	55.1 **
size	1.52	0.49
interaction	1.32	1.35
Shape means (ranking):		
circular	4.15 (1)	4.30 (1)
square	2.80 (2)	3.10 (2)
rectangular	2.38 (2)	2.78 (2)
Size means (ranking):		
100 mm	3.23 (NS)	3.47 (NS)
120 mm	3.30 (NS)	3.43 (NS)
140 mm	3.03 (NS)	3.40 (NS)
160 mm	2.87 (NS)	3.27 (NS)
<u>ELDERLY SUBJECTS</u>		
F-values:		
shape	16.1 **	21.4 **
size	6.22 **	7.66 **
interaction	2.63 *	2.62 *
Shape means (ranking):		
circular	3.93 (I)	4.03 (I)
square	2.98 (I)	3.23 (I)
rectangular	2.75 (I)	2.85 (I)
Size means (ranking):		
100 mm	3.10 (I)	3.43 (I)
120 mm	3.60 (I)	3.70 (I)
140 mm	3.53 (I)	3.57 (I)
160 mm	2.63 (I)	2.77 (I)

NOTE: * indicates significant difference between means at $p=0.05$
 ** indicates significant difference between means at $p=0.01$
 NS indicates no significant difference between means
 I indicates that means cannot be ranked, due to interaction

TABLE 3.4 - ANOVA of Comfort Ratings for Handrail Configurations

		YOUNG SUBJECTS		ELDERLY SUBJECTS	
		Grip Comfort	Slide Comfort	Grip Comfort	Slide Comfort
F-values:		11.8 **	9.10 **	10.8 **	7.51 **
Mean values (ranking):					
circular	100	4.0 (1)	4.1 (1)	3.0 (2)	3.5 (1)
	120	4.2 (1)	4.4 (1)	4.6 (1)	4.5 (1)
	140	4.3 (1)	4.4 (1)	4.7 (1)	4.6 (1)
	160	4.1 (1)	4.3 (1)	3.4 (1)	3.5 (1)
square	100	3.4 (2)	3.6 (1)	3.1 (2)	3.3 (1)
	120	2.9 (2)	3.0 (2)	3.2 (2)	3.6 (1)
	140	2.6 (2)	3.0 (2)	3.1 (2)	3.2 (2)
	160	2.3 (2)	2.8 (2)	2.5 (2)	2.8 (2)
rectangular	100	2.3 (2)	2.7 (2)	3.2 (2)	3.5 (1)
	120	2.8 (2)	2.9 (2)	3.0 (2)	3.0 (2)
	140	2.2 (2)	2.8 (2)	2.8 (2)	2.9 (2)
	160	2.2 (2)	2.7 (2)	2.0 (2)	2.0 (2)
oval		3.8 (1)	4.0 (1)	4.2 (1)	4.1 (1)
decorative		1.8 (3)	2.8 (2)	2.0 (2)	2.5 (2)
rect-1x6		1.8 (3)	3.2 (2)	1.5 (3)	2.4 (2)
rect-2x4		2.0 (3)	3.5 (1)	1.7 (3)	2.5 (2)

NOTE: * indicates significant difference between means at $p=0.05$
 ** indicates significant difference between means at $p=0.01$

TABLE 3.5 - Summary of Design Estimates for Handrail Shape and Size

VARIABLE	HANDRAIL SHAPE	ACCEPTABLE HANDRAIL DESIGNS * YOUNG ELDERLY								
<u>FORCE/MOMENT GENERATION</u>										
Mb-Backward Moment	circular	10	12	14	16		10	12	14	xx
	square	10	12	xx	16		10	12	14	xx
	rectangular	10	12	14	16		10	xx	xx	16
	others	ovl	xx	xx	xx		xx	xx	xx	xx
Mf-Forward Moment	circular	10	12	14	16		10	12	14	16
	square	10	12	xx	16		10	12	14	16
	rectangular	xx	xx	14	16		10	12	14	16
	others	ovl	xx	xx	xx		xx	xx	xx	xx
Fb-Backward Force	circular	10	12	14	16		10	12	14	xx
	square	10	12	xx	16		10	12	14	16
	rectangular	10	12	xx	16		10	12	14	16
	others	ovl	xx	xx	xx		ovl	xx	xx	xx
Ff-Forward Force	circular	10	12	14	16		10	12	14	16
	square	10	12	14	16		10	12	14	16
	rectangular	10	12	14	16		10	12	14	16
	others	ovl	xx	xx	xx		ovl	xx	xx	xx
Fu-Upward Force	circular	xx	12	xx	xx		xx	12	14	16
	square	xx	xx	xx	xx		10	xx	14	16
	rectangular	xx	xx	xx	16		xx	xx	xx	-16
	others	ovl	xx	xx	xx		xx	xx	xx	xx
<u>PREFERENCE</u>										
Grip Comfort	circular	10	12	14	16		10	12	14	16
	square	10	12	xx	xx		10	12	xx	xx
	rectangular	xx	12	xx	xx		xx	12	xx	xx
	others	ovl	xx	xx	xx		ovl	xx	xx	xx
Slide Comfort	circular	10	12	14	16		10	12	14	16
	square	10	12	14	xx		10	12	14	16
	rectangular	10	12	14	xx		10	12	xx	xx
	others	ovl	dec	2x4	1x6		ovl	xx	xx	xx
Avoidance	circular	10	12	14	16		10	12	14	16
	square	10	12	14	16		10	12	14	16
	rectangular	10	12	14	16		10	12	14	xx
	others	ovl	xx	2x4	xx		ovl	xx	xx	xx
<u>OVERALL</u>										
	circular	xx	12	xx	xx		xx	12	14	xx
	square	xx	xx	xx	xx		10	xx	xx	xx
	rectangular	xx	xx	xx	xx		xx	xx	xx	xx
	others	ovl	xx	xx	xx		xx	xx	xx	xx

* NOTE: xx = not acceptable; 10,12,14 or 16 = size (cm) that is acceptable
ovl = oval; dec = decorative

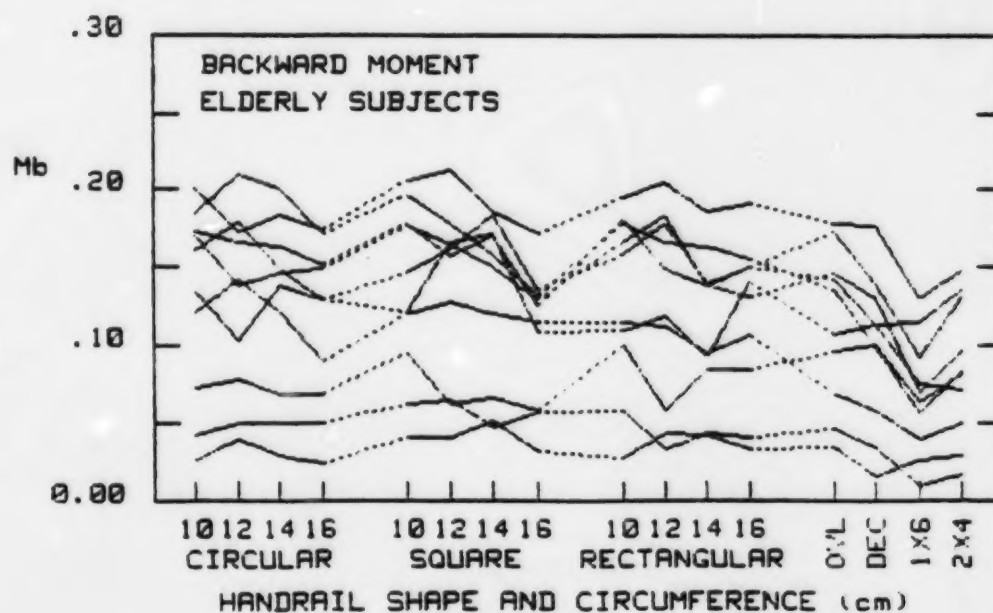
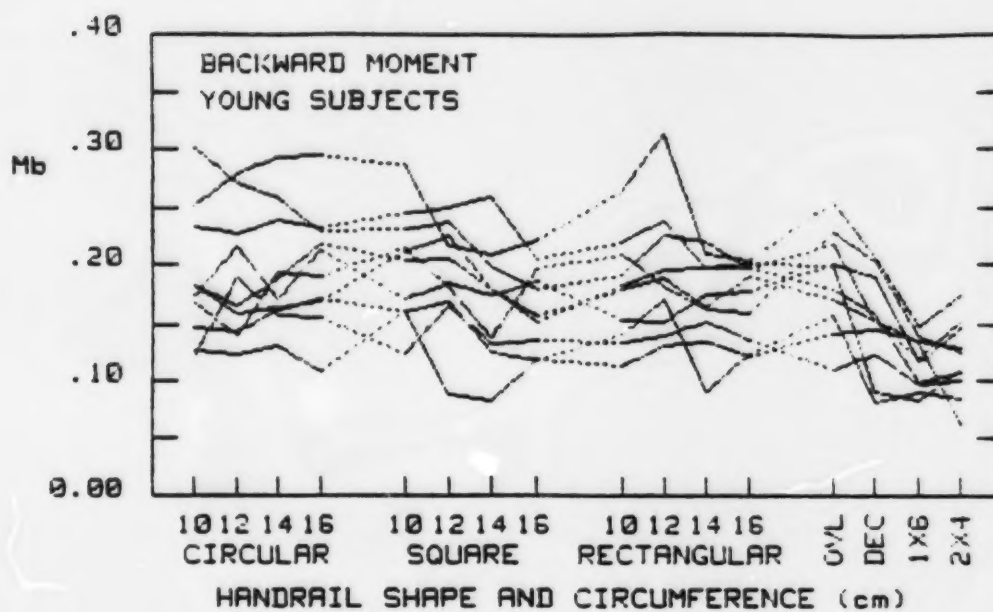


Figure 3.1 Backward Moment versus Handrail Design - Data

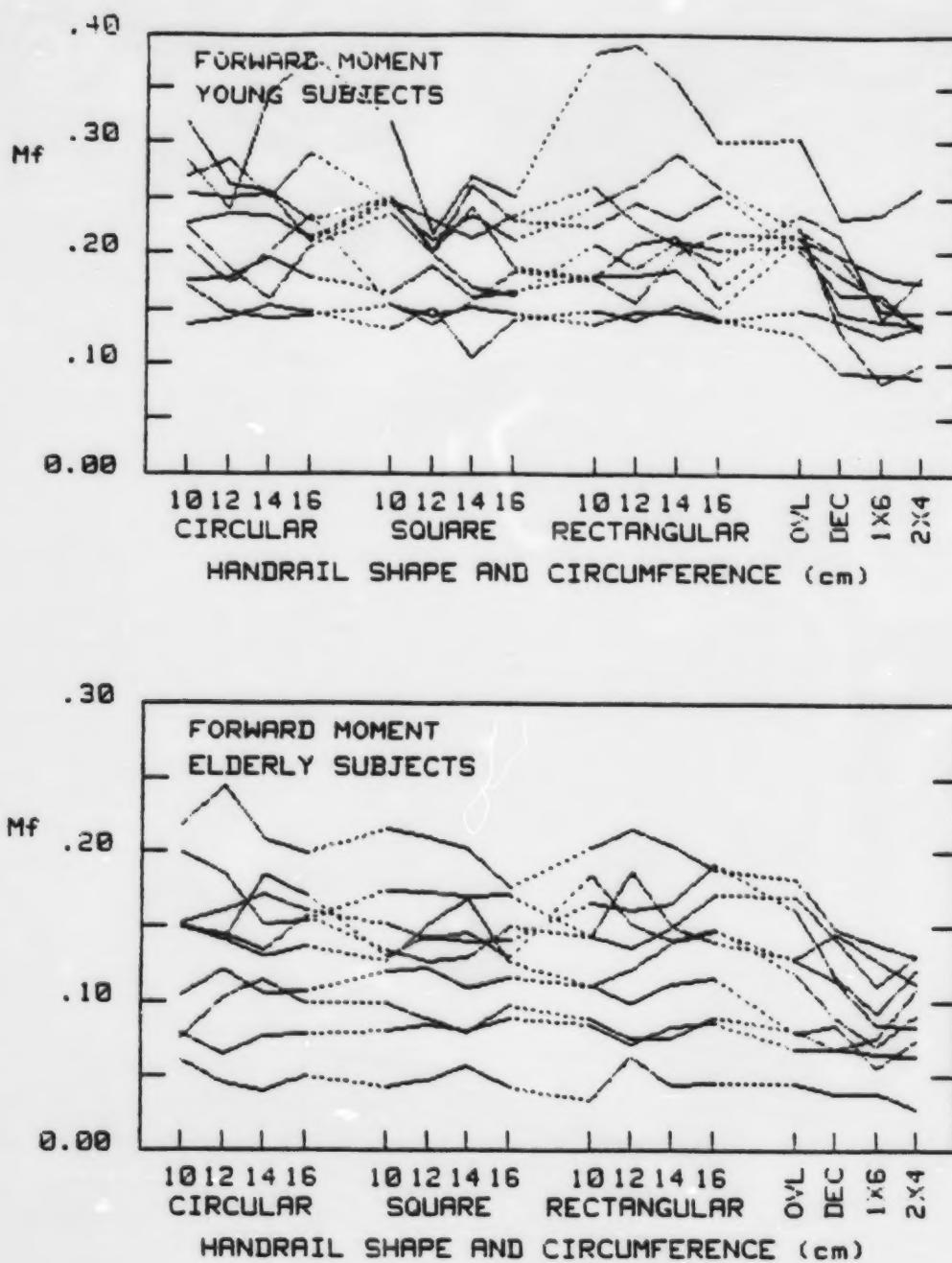


Figure 3.2 Forward Moment versus Handrail Design - Data

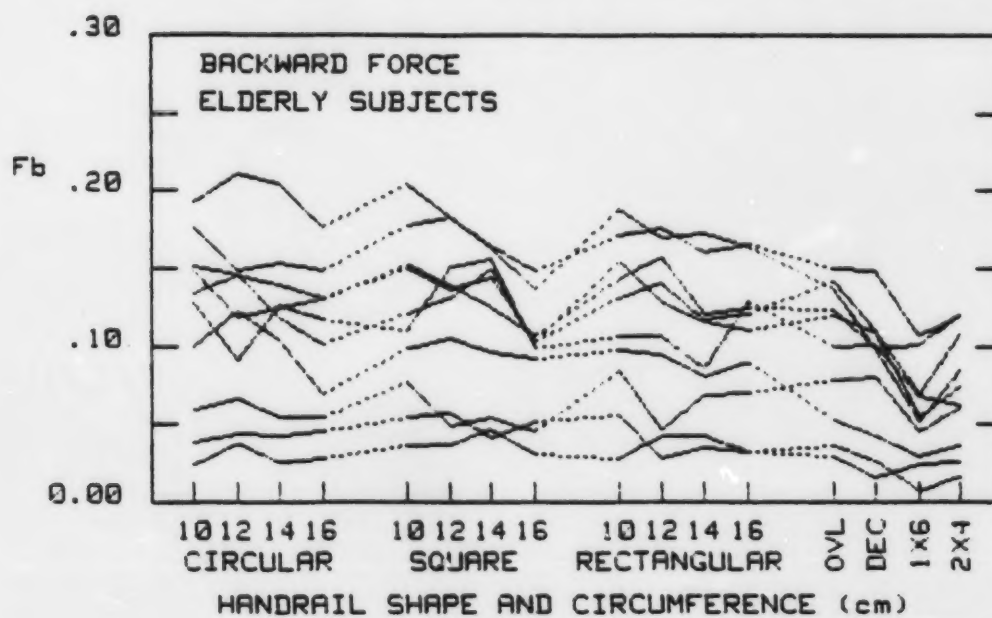
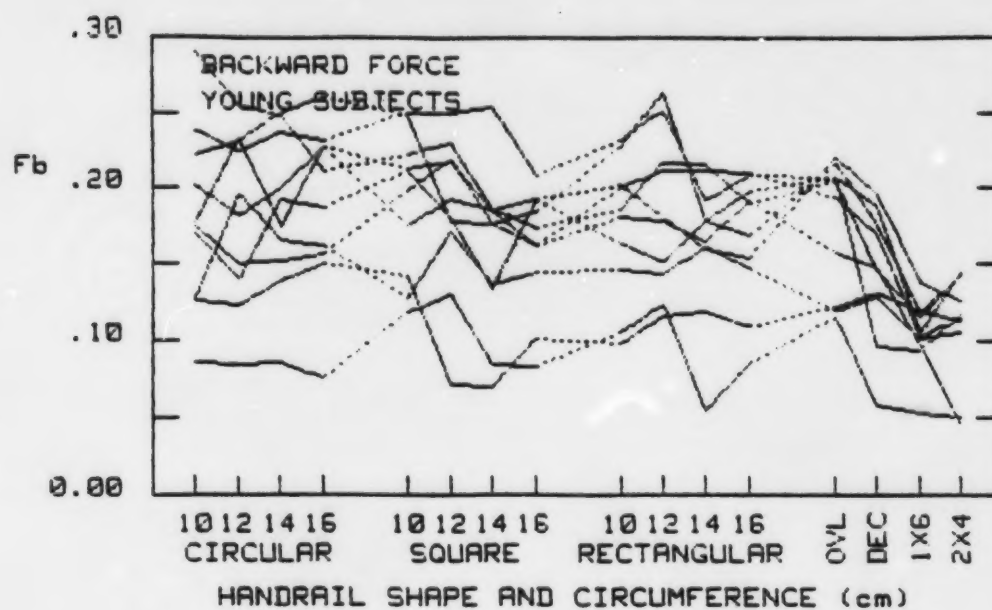


Figure 3.3 Backward Force versus Handrail Design - Data

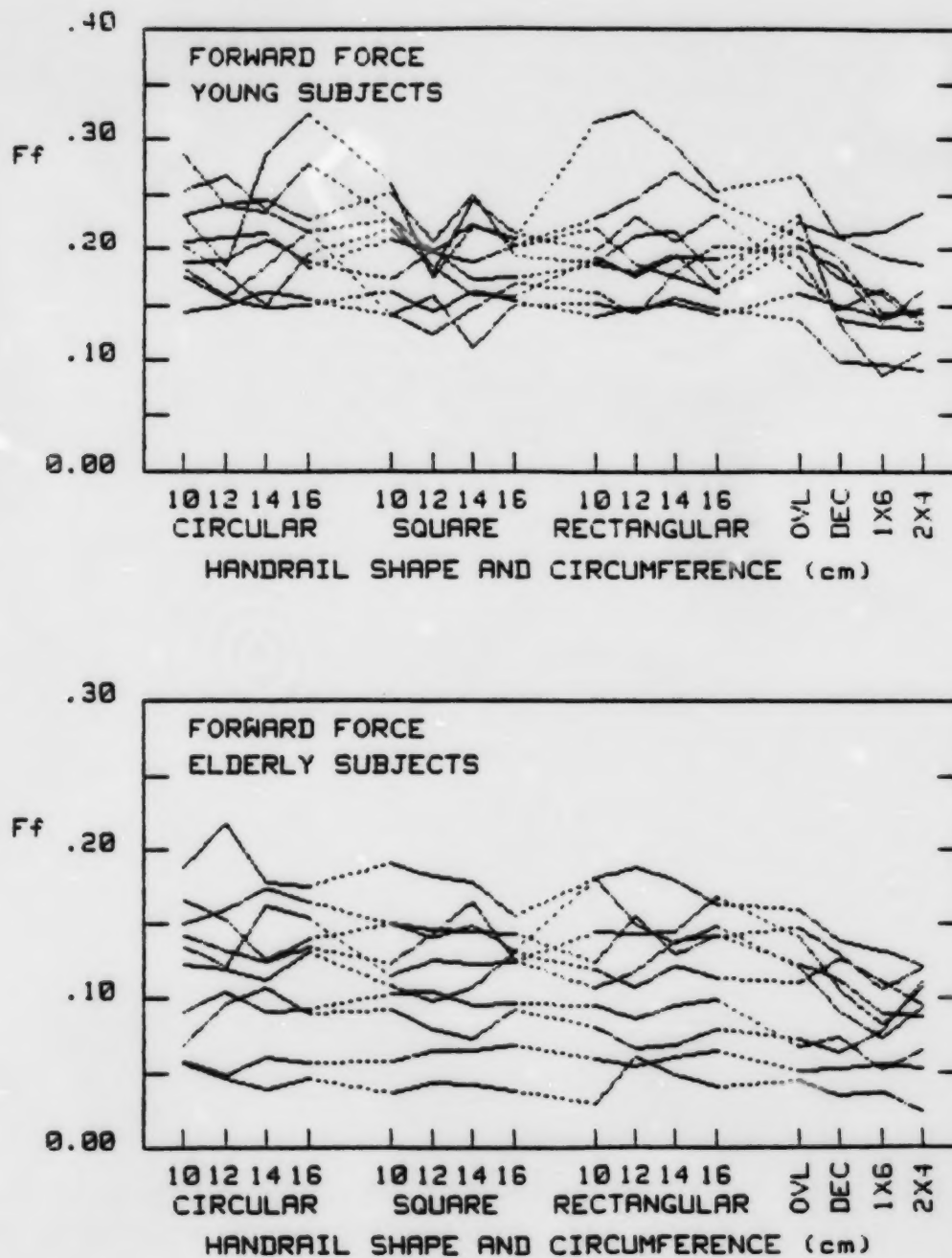


Figure 3.4 Forward Force versus Handrail Design - Data

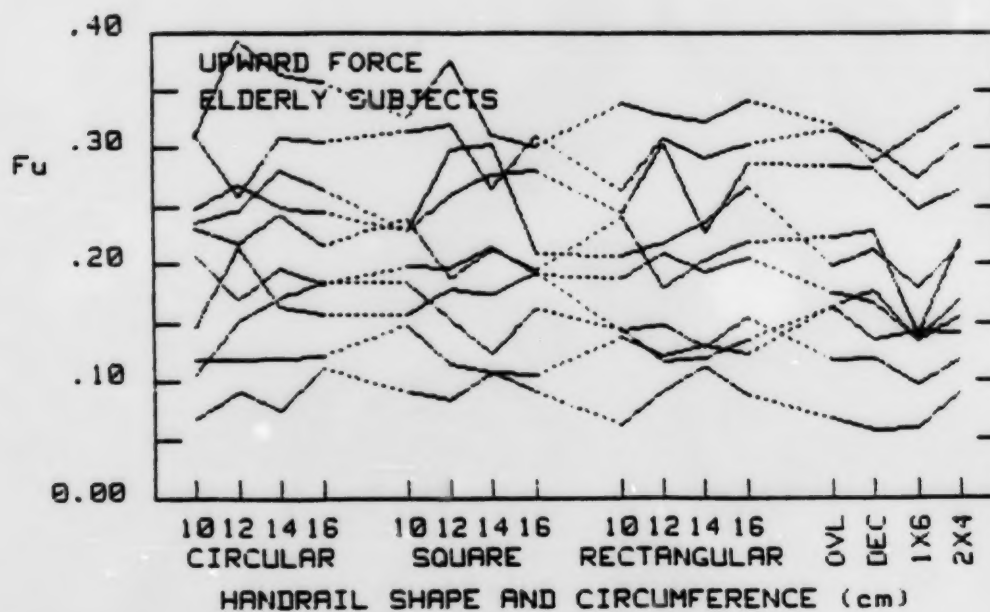
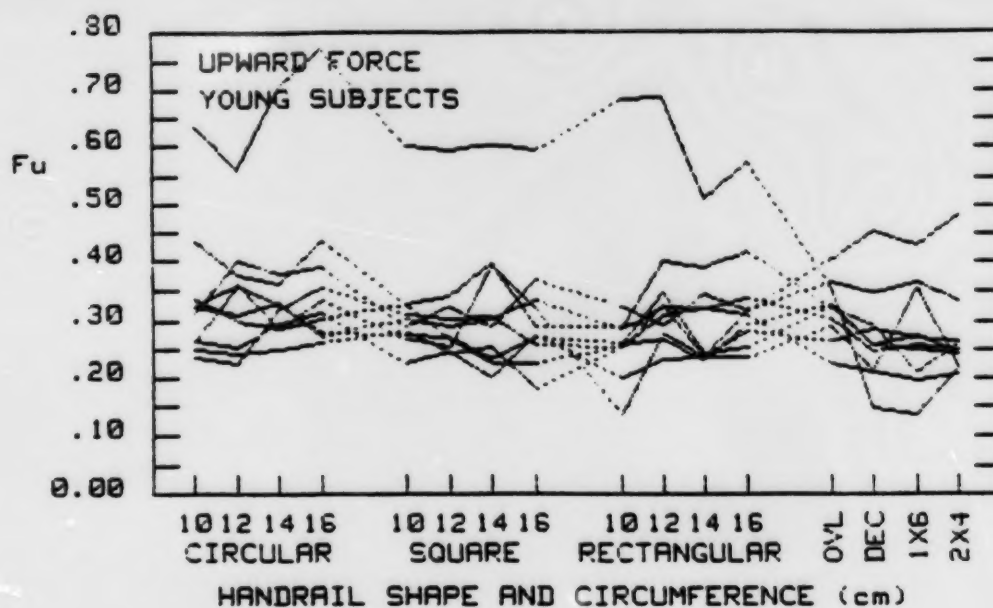


Figure 3.5 Upward Force versus Handrail Design - Data

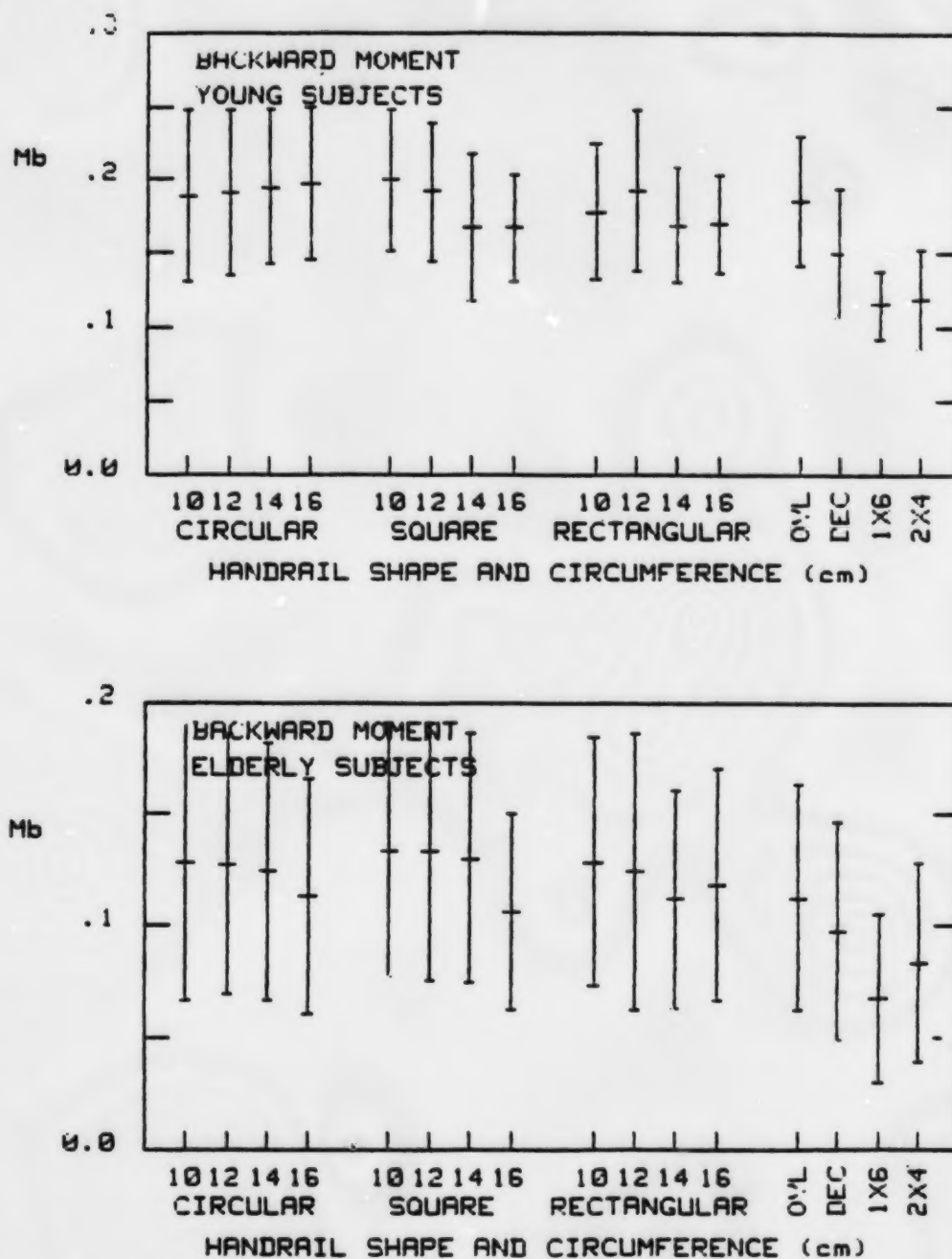


Figure 3.6 Backward Moment versus Handrail Design - Mean Values

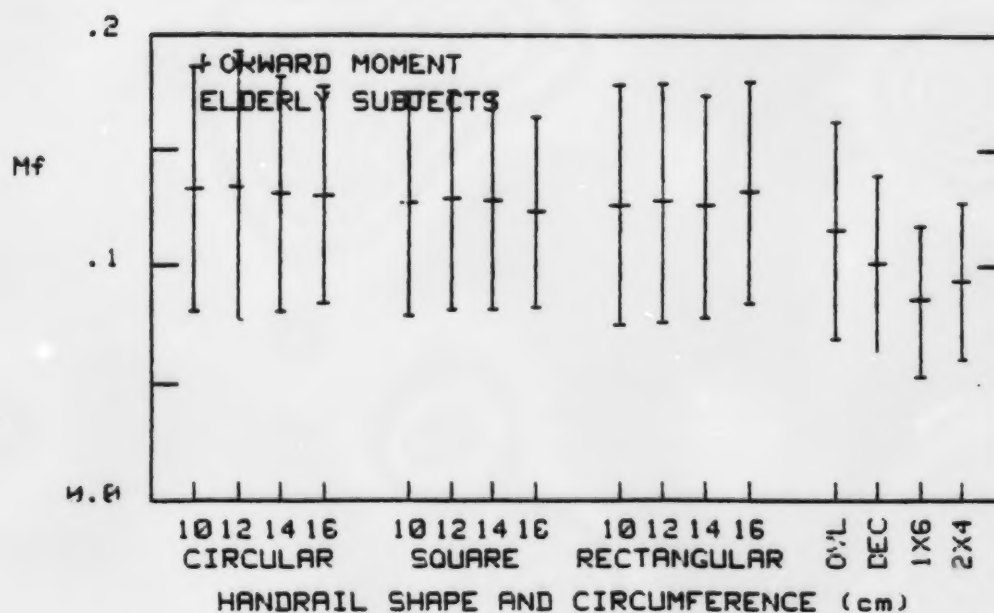
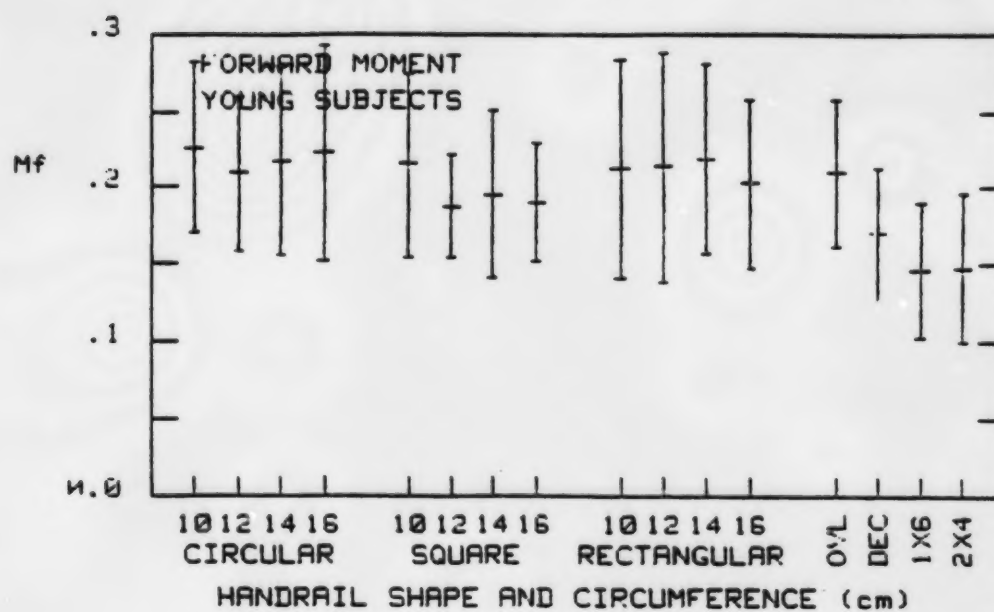


Figure 3.7 Forward Moment versus Handrail Design - Mean Values

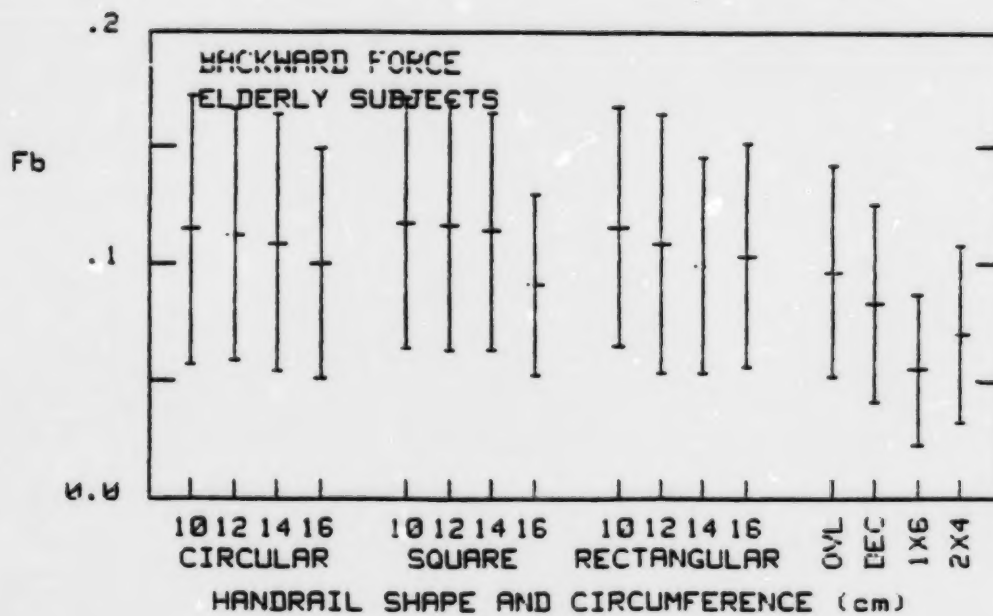
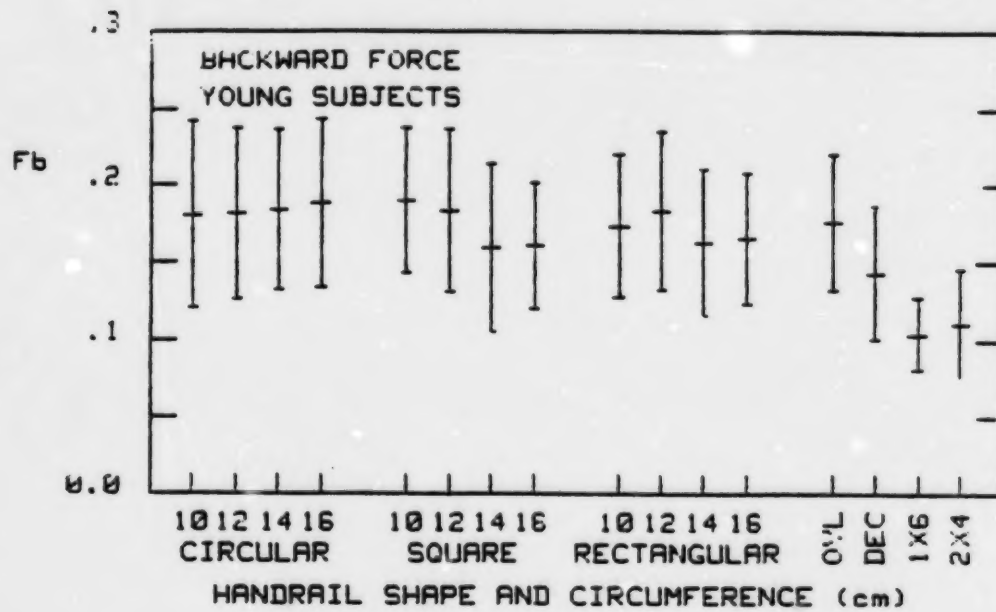


Figure 3.8 Backward Force versus Handrail Design - Mean Values

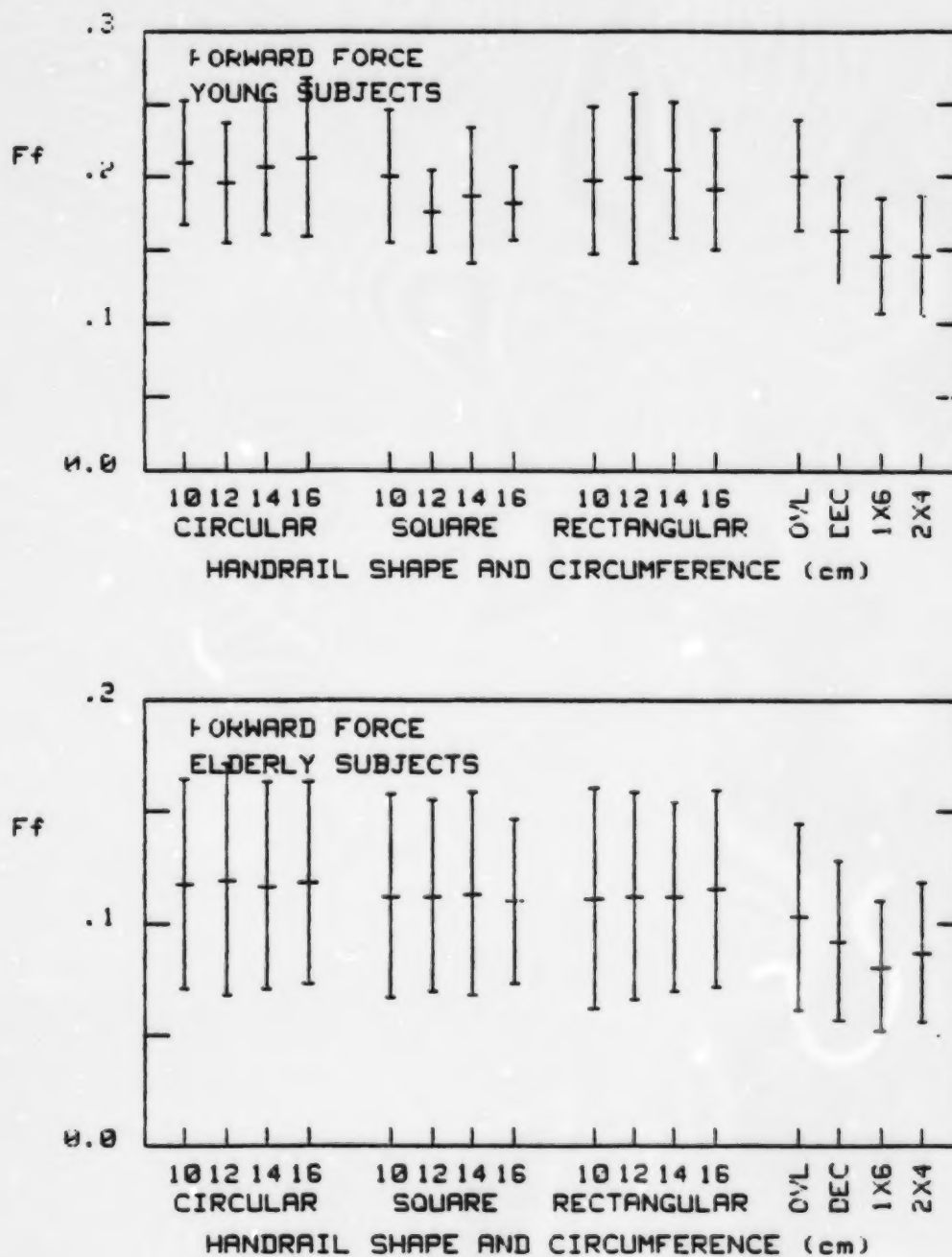


Figure 3.9 Forward Force versus Handrail Design - Mean Values

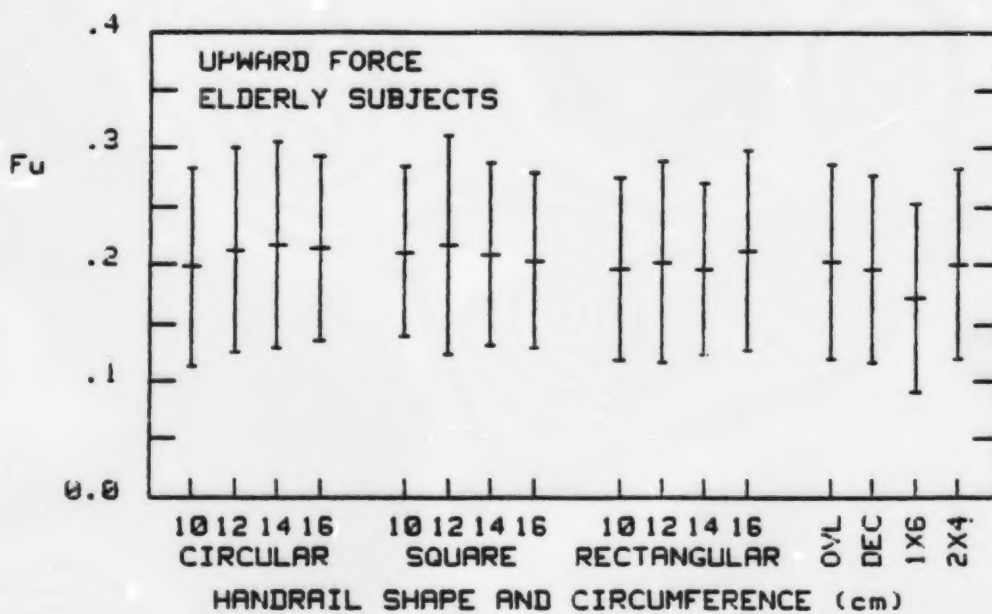
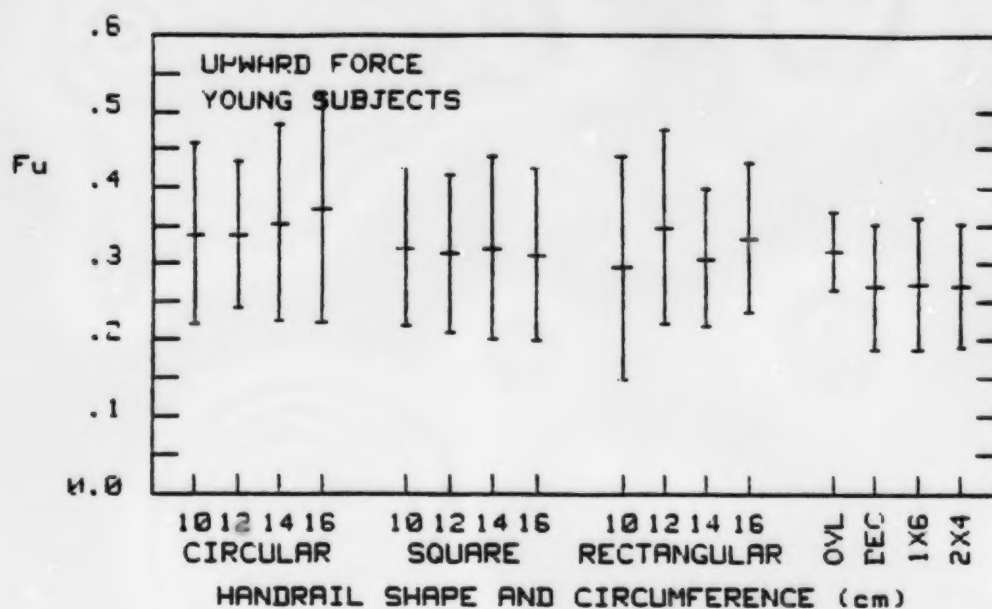


Figure 3.10 Upward Force versus Handrail Design - Mean Values

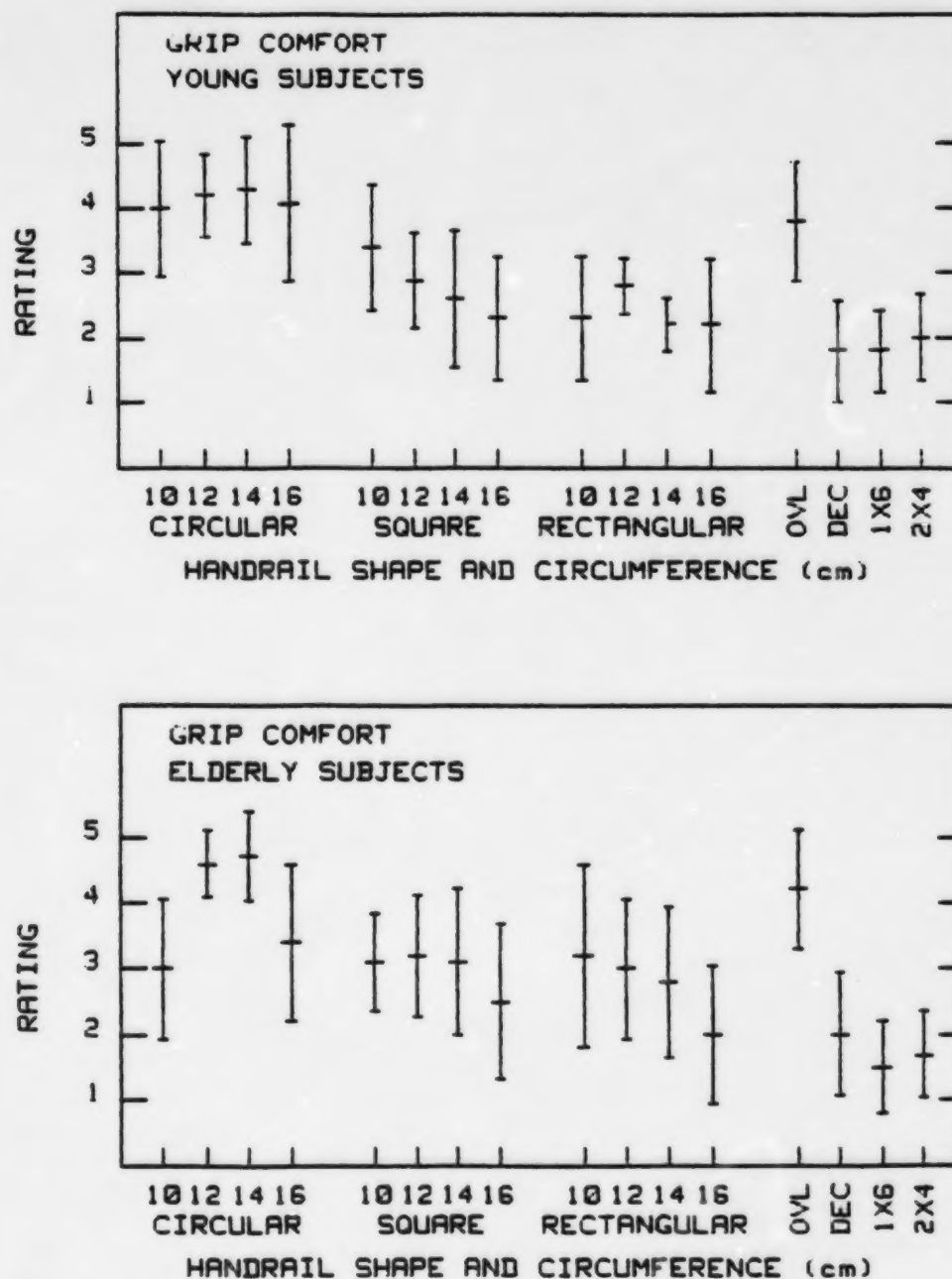


Figure 3.11 Grip Comfort versus Handrail Design

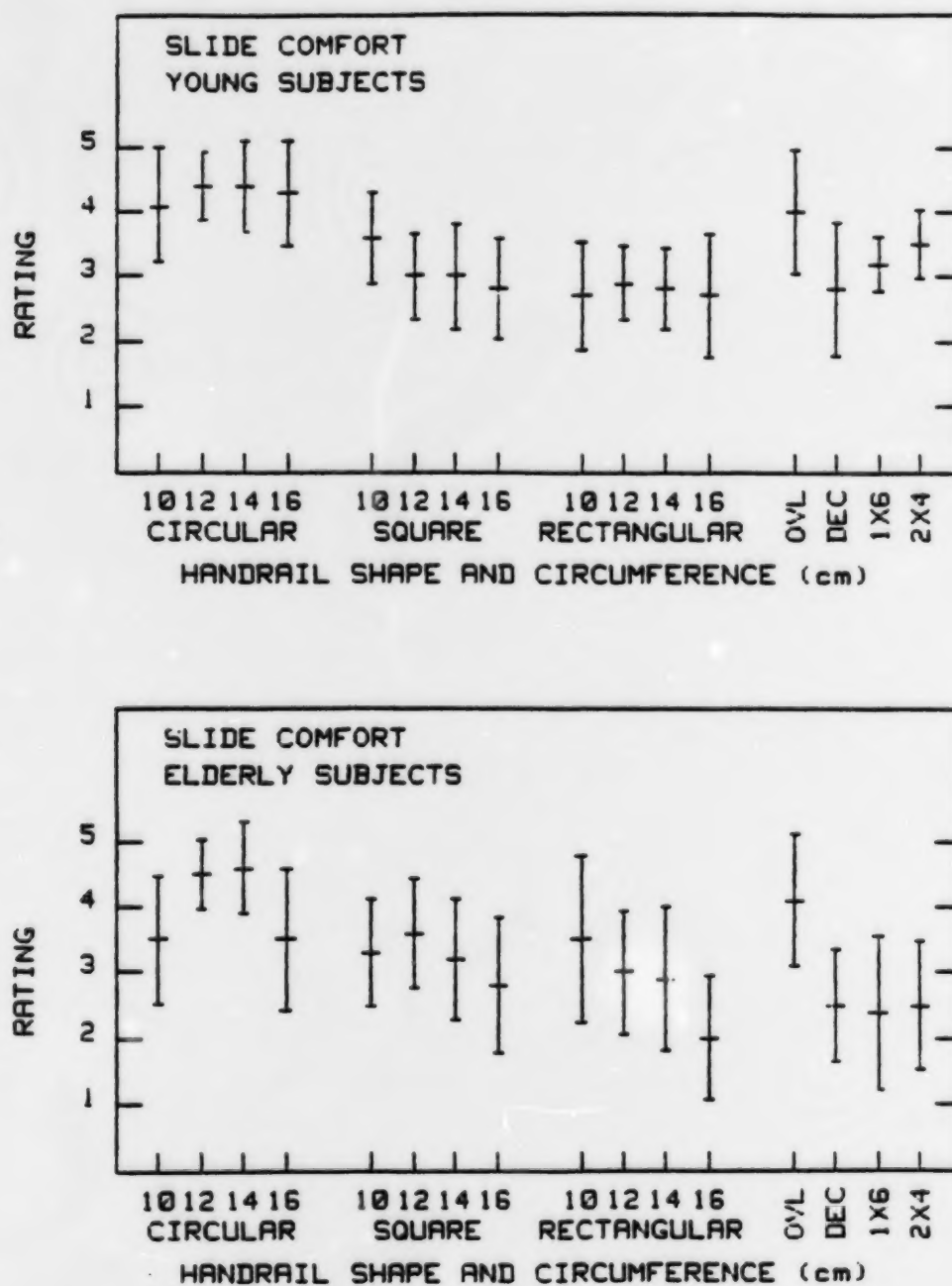


Figure 3.12 Slide Comfort versus Handrail Design

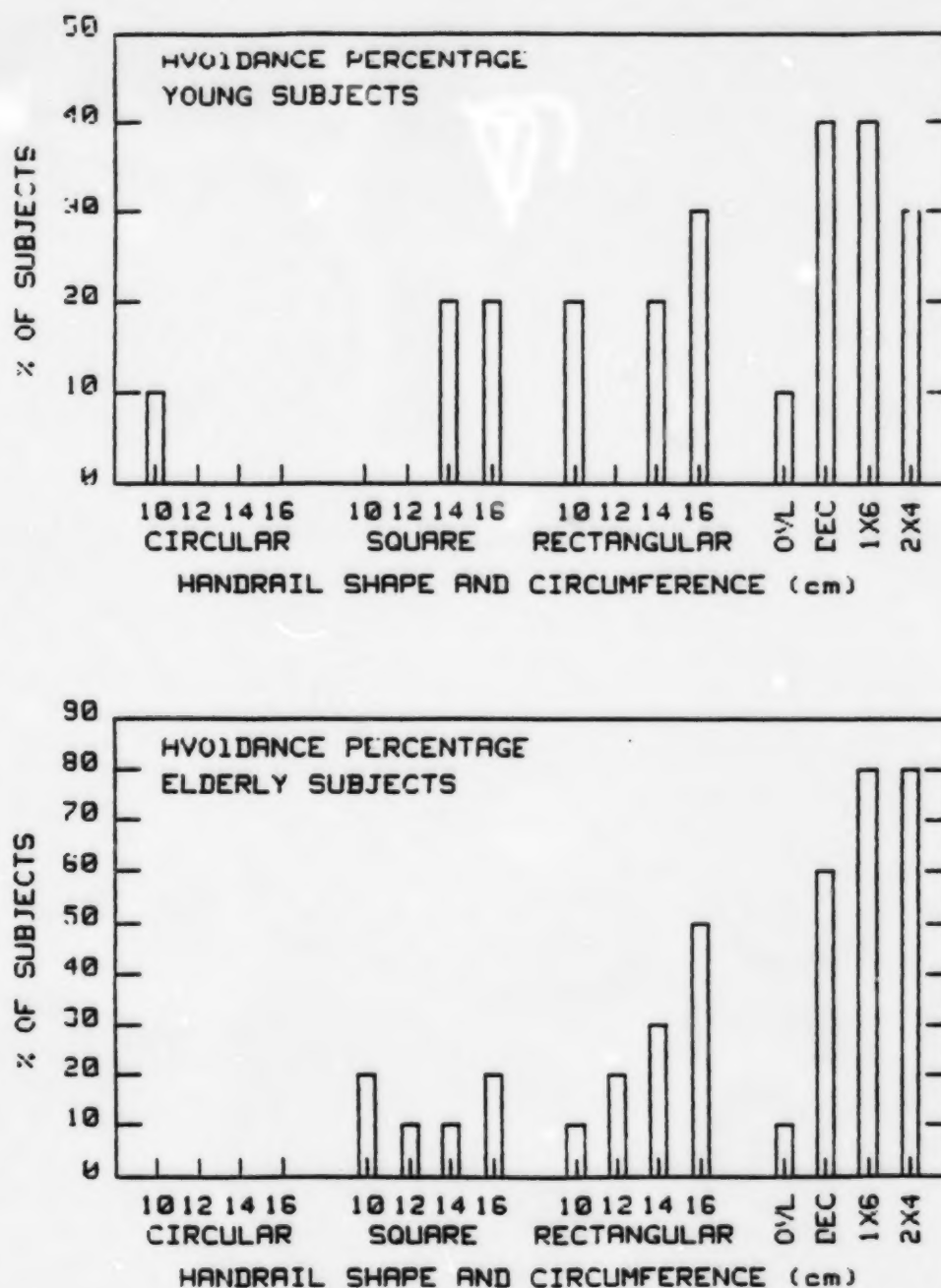


Figure 3.13 Avoidance Percentage versus Handrail Design

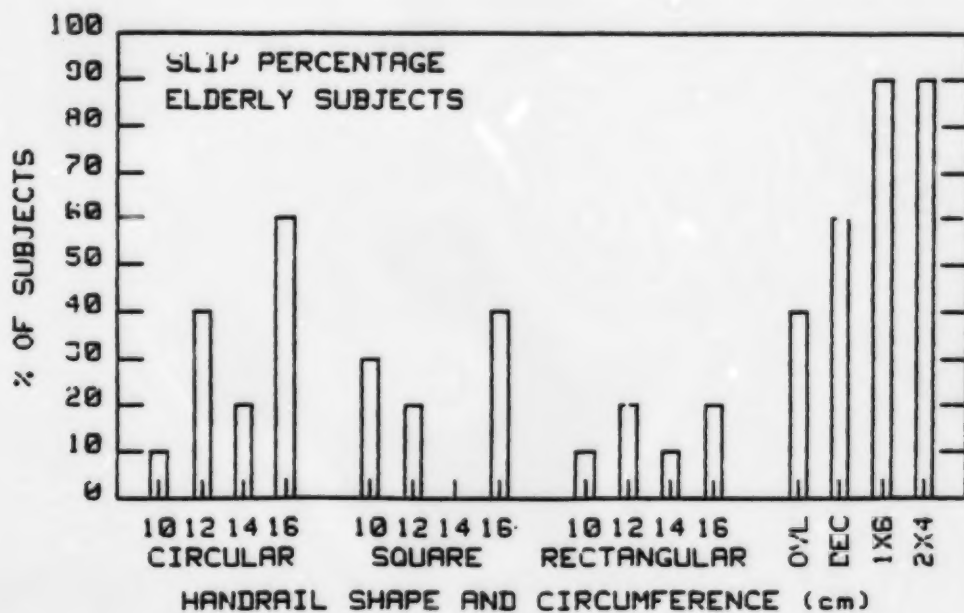
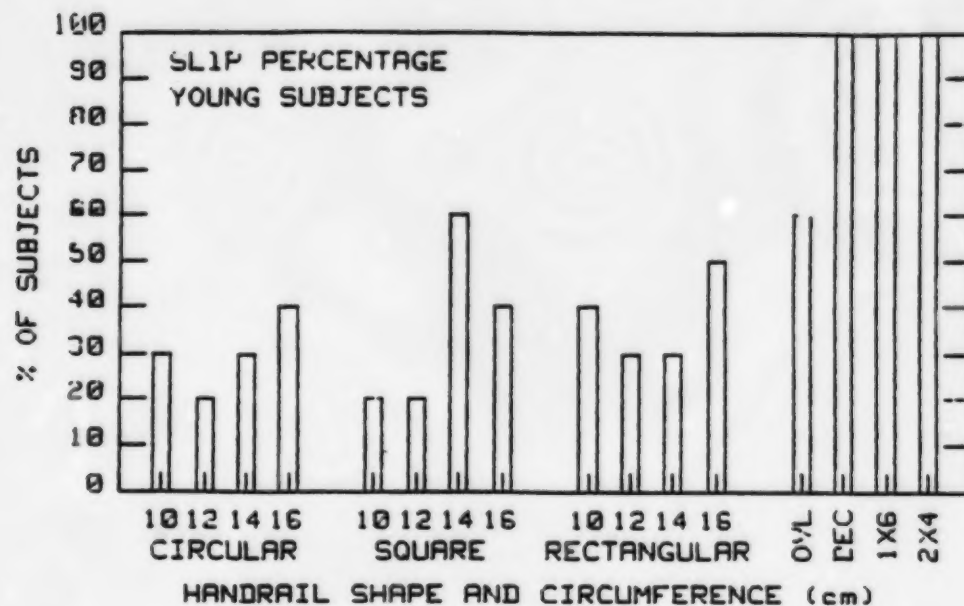


Figure 3.14 Slip Percentage versus Handrail Design

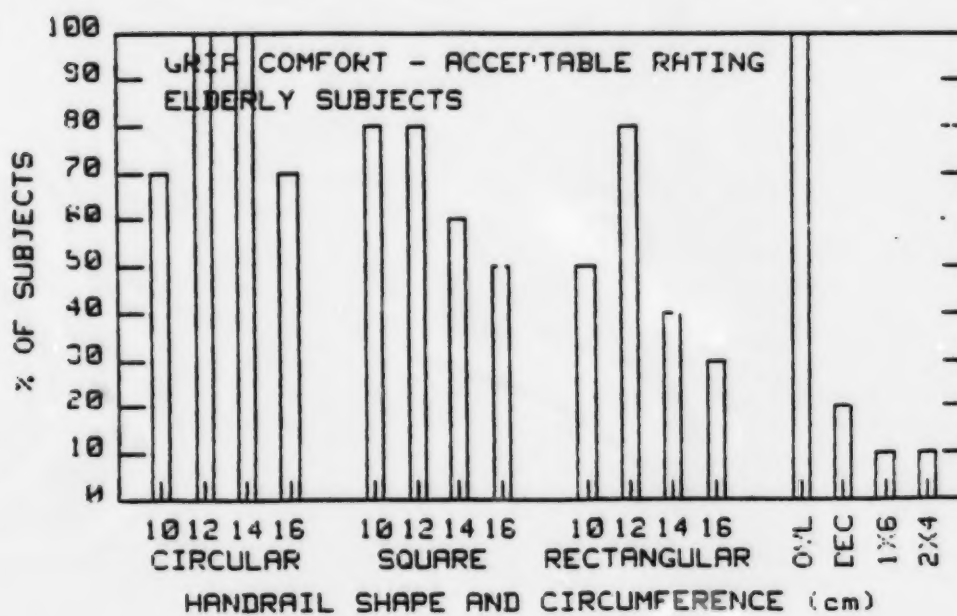
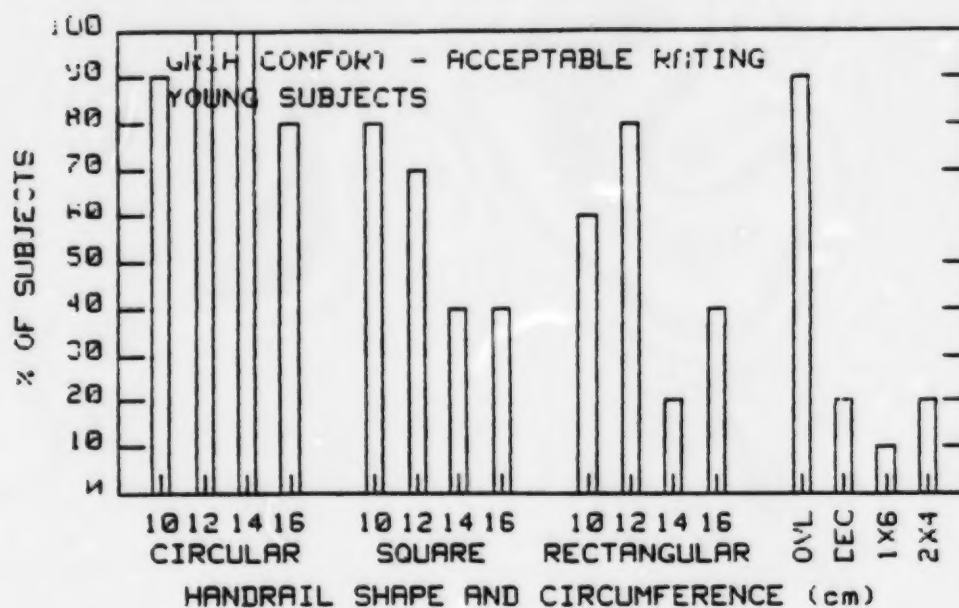


Figure 3.15 Grip Comfort - Percentage with Acceptable Ratings

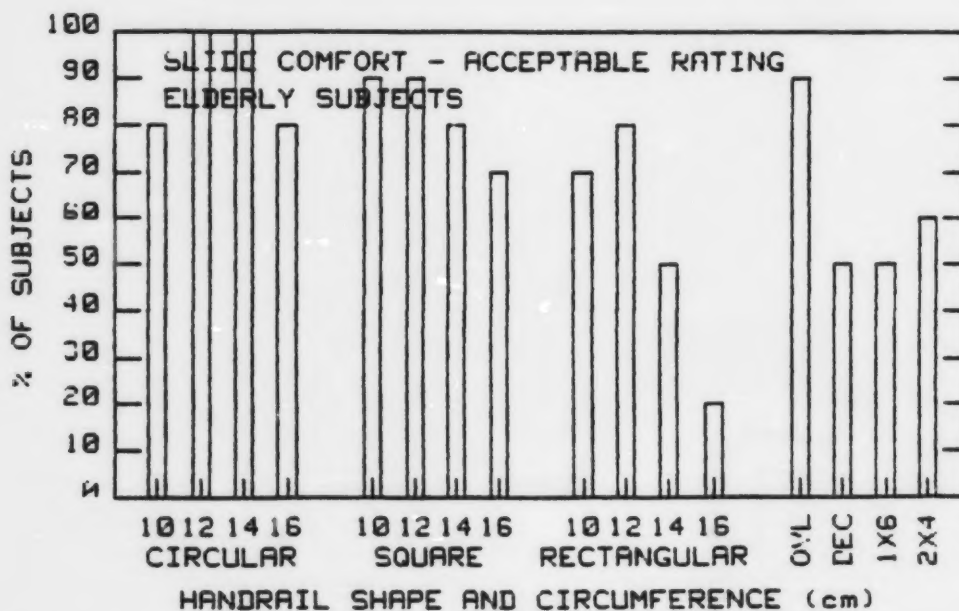
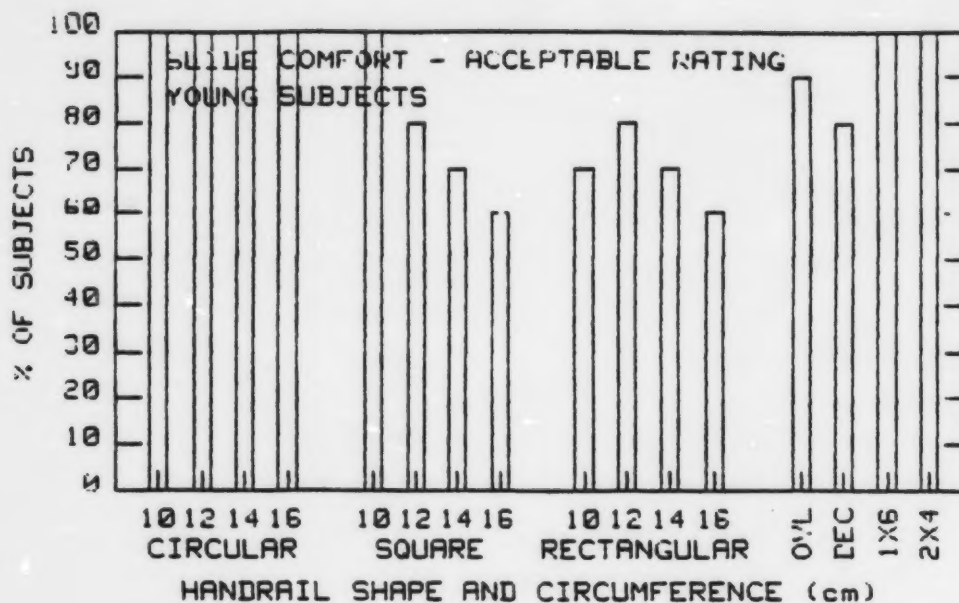


Figure 3.16 Slide Comfort - Percentage with Acceptable Ratings

IV RESULTS - HANDRAIL SURFACE TEXTURE

4.1 Force and Moment Generation

The normalized force and moment data for the various handrail surfaces are plotted in Figures 4.1 to 4.5. Each plot represents the variation of a given normalized force or moment as a function of the handrail surface. The result for each subject is plotted as a line to allow trends to be identified. Results for the young and the elderly subjects have been plotted on separate graphs.

The mean normalized force and moment values (and corresponding standard deviations) are shown in Figures 4.6 to 4.10. These plots represent the distribution of force/moment generating ability occurring within each age group as a function of handrail surface.

The results of the analysis of variance are summarized in Table 4.1. Each age group was analyzed separately and each of the five normalized force and moment variables was analyzed separately. For each of the eight surface textures, the mean force/moment values are shown. The ranking of these values, based on differences significant at $p=0.05$, is also shown.

For the young subjects, there were some significant differences between the mean forces and moments generated using the different handrail surfaces. For variables M_f , F_b , and F_f , the chrome and/or acrylic-vinyl surfaces were found to show significantly lower values.

The elderly subjects showed some significant differences as well. For these subjects, the chrome, acrylic-vinyl and foam handrails were found to have significantly lower values for variables M_b , F_b and F_u .

4.2 Grip and Sliding Comfort Ratings

The mean grip comfort and sliding comfort ratings (and associated standard deviations) are shown in Figures 4.11 and 4.12. These values, plotted as a function of handrail surface, represent the preferences of the two age groups.

The results of the analysis of variance of the comfort ratings are summarized in Table 4.4. Each age group was analyzed separately and the two comfort ratings were analyzed separately. For each of the eight surface textures, the mean ratings and rankings (based on differences significant at $p=0.05$) are shown.

For both age groups, there were some significant differences ($p=0.01$) between the comfort ratings of the different handrail surfaces. In all cases, the "rough" surface was rated significantly poorer than the other surfaces tested. The foam handrail was rated poorer only for sliding comfort, and only by the young subjects.

4.3 Avoidance

In Figure 4.13, the percentage of subjects who stated that they would avoid holding or sliding their hand along a particular handrail surface is plotted as a function of handrail surface. These values include those subjects who stated that they would avoid the surface in any circumstance as well as those who stated that they would avoid the surface except on steep stairways.

It is evident from the plots that few subjects would avoid the handrail surfaces tested. The exceptions are the "foam" handrail and the "rough" handrail. Some subjects found the frictional heat generated by sliding their hand along the foam handrail to be objectionable. A large number of subjects found the surface of the "rough" handrail to be excessively rough.

4.4 Slippage

The percentage of subjects who detected slipping of their hands while pushing or pulling on the handrail is plotted as a function of handrail surface in Figure 4.14. While there was some incidence of slippage for all of the surfaces, the chrome and acrylic-vinyl surfaces showed the highest incidence of slippage.

4.5 Estimation of Optimal Design Values

In Figures 4.6 to 4.10, the lower end of each data bar represents the estimate for the 17th-percentile moment or force. Table 4.3 lists the handrail surfaces that have the highest 17th-percentile forces and moment. Those surfaces deemed to be acceptable were selected using the method described in Section 2.5. The table also lists those surfaces deemed to be acceptable on the basis of grip comfort, sliding comfort and avoidance, using the criteria of acceptability discussed in Section 2.5. (In connection with this analysis, Figures 4.15 and 4.16 show the percentage of subjects who rated each handrail surface "acceptable" or better.)

Overall, the recommended surfaces are those which were found to be acceptable on the basis of force/moment generation (for all five forces and moments) and on the basis of comfort (grip, slip and avoidance). For both the young and elderly subjects, the recommended surfaces are the glossy, enamel and vinyl surfaces.

TABLE 4.1 - ANOVA of Force/Moment Generation for Handrail Surfaces

	Mb Backward Moment	Mf Forward Moment	Fb Backward Force	Ff Forward Force	Fu Upward Force
<u>YOUNG SUBJECTS</u>					
F-values:	2.00	2.68 *	2.58 *	2.14 *	0.92
Mean values (ranking):					
matte	0.215 (NS)	0.240 (1)	0.196 (1)	0.219 (1)	0.340 (NS)
glossy	0.234 (NS)	0.230 (1)	0.218 (1)	0.214 (1)	0.350 (NS)
rough	0.218 (NS)	0.231 (1)	0.203 (1)	0.213 (1)	0.342 (NS)
chrome	0.204 (NS)	0.208 (2)	0.188 (1)	0.193 (2)	0.325 (NS)
enamel	0.239 (NS)	0.249 (1)	0.220 (1)	0.228 (1)	0.377 (NS)
vinyl	0.229 (NS)	0.240 (1)	0.211 (1)	0.225 (1)	0.363 (NS)
acrylic	0.198 (NS)	0.217 (2)	0.177 (2)	0.203 (1)	0.351 (NS)
foam	0.213 (NS)	0.234 (1)	0.196 (1)	0.217 (1)	0.367 (NS)
<u>ELDERLY SUBJECTS</u>					
F-values:	5.93 **	1.90	5.76 **	1.56	3.27 **
Mean values (ranking):					
matte	0.127 (1)	0.130 (NS)	0.106 (1)	0.113 (NS)	0.223 (1)
glossy	0.133 (1)	0.127 (NS)	0.115 (1)	0.112 (NS)	0.211 (1)
rough	0.123 (1)	0.128 (NS)	0.106 (1)	0.112 (NS)	0.214 (1)
chrome	0.116 (2)	0.117 (NS)	0.098 (2)	0.103 (NS)	0.191 (2)
enamel	0.148 (1)	0.133 (NS)	0.127 (1)	0.116 (NS)	0.232 (1)
vinyl	0.127 (1)	0.135 (NS)	0.107 (1)	0.117 (NS)	0.223 (1)
acrylic	0.101 (2)	0.119 (NS)	0.084 (2)	0.106 (NS)	0.193 (2)
foam	0.113 (2)	0.122 (NS)	0.096 (2)	0.108 (NS)	0.199 (2)

NOTE: * indicates significant difference between means at $p=0.05$
 ** indicates significant difference between means at $p=0.01$
 NS indicates no significant difference between means

TABLE 4.2 - ANOVA of Comfort Ratings for Handrail Surfaces

	YOUNG SUBJECTS		ELDERLY SUBJECTS	
	Grip Comfort	Slide Comfort	Grip Comfort	Slide Comfort
F-values:	10.5 **	9.89 **	9.19 **	10.8 **
Mean values (ranking):				
matte	4.5 (1)	4.5 (1)	4.2 (1)	4.1 (1)
glossy	4.3 (1)	3.9 (1)	4.6 (1)	3.9 (1)
rough	2.0 (2)	1.3 (3)	1.7 (2)	1.1 (2)
chrome	4.3 (1)	3.4 (1)	4.3 (1)	3.6 (1)
enamel	4.2 (1)	3.6 (1)	4.4 (1)	3.9 (1)
vinyl	4.5 (1)	3.9 (1)	4.2 (1)	3.9 (1)
acrylic	3.7 (1)	3.7 (1)	3.8 (1)	3.6 (1)
foam	4.7 (1)	3.1 (2)	4.1 (1)	2.8 (1)

NOTE: * indicates significant difference between means at $p=0.05$
 ** indicates significant difference between means at $p=0.01$

TABLE 4.3 - Summary of Design Estimates for Handrail Surface Texture

VARIABLE	ACCEPTABLE HANDRAIL DESIGNS *															
	YOUNG SUBJECTS								ELDERLY SUBJECTS							
	SURFACE **								SURFACE **							
	M	G	R	C	E	V	A	F	M	G	R	C	E	V	A	F
<u>FORCE/MOMENT GENERATION</u>																
Mb-Backward Moment	x	A	x	x	A	A	x	x	x	A	x	x	A	A	x	x
Mf-Forward Moment	A	A	x	x	A	A	x	A	A	A	x	A	A	A	A	x
Fb-Backward Force	x	A	x	x	A	A	x	x	A	A	x	x	A	A	x	x
Ff-Forward Force	A	A	x	x	A	A	A	A	A	A	x	A	A	A	A	x
Fu-Upward Force	A	A	x	x	A	A	A	x	A	A	x	x	A	A	x	x
<u>PREFERENCE</u>																
Grip Comfort	A	A	x	A	A	A	A	A	A	A	x	A	A	A	A	A
Slide Comfort	A	A	x	A	A	A	A	x	A	A	x	A	A	A	A	x
Avoidance	A	A	x	A	A	A	A	A	A	A	x	A	A	A	A	x
<u>OVERALL</u>																
	x	A	x	x	A	A	x	x	x	A	x	x	A	A	x	x

Note: * (1) x = not acceptable; A = acceptable

** (2) Handrail Surface Textures:

M = matte

R = rough

E = enamel

A = acrylic vinyl

G = glossy

C = chrome

V = vinyl

F = foam

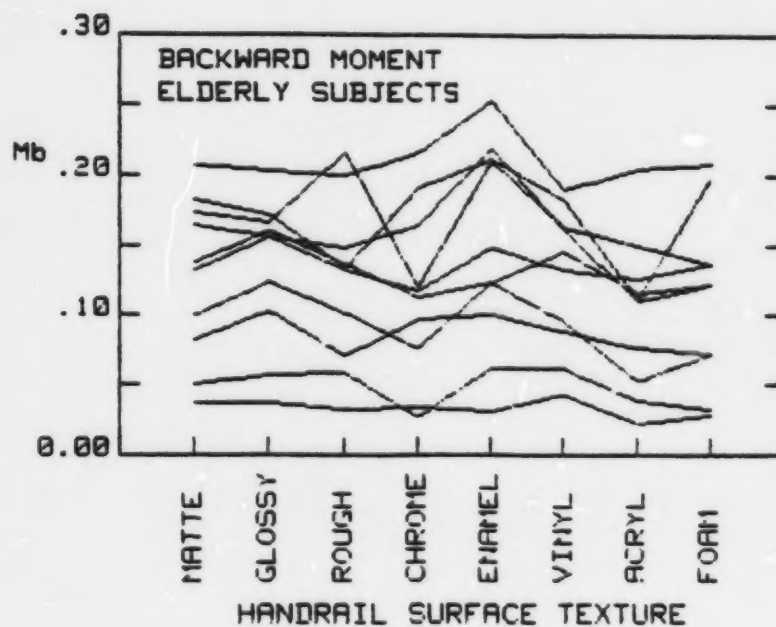
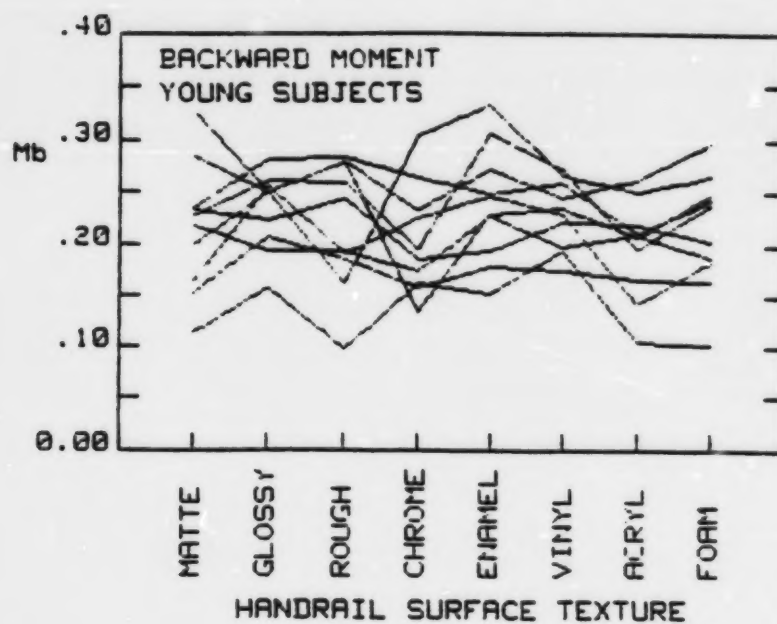


Figure 4.1 Backward Moment versus Handrail Surface - Data

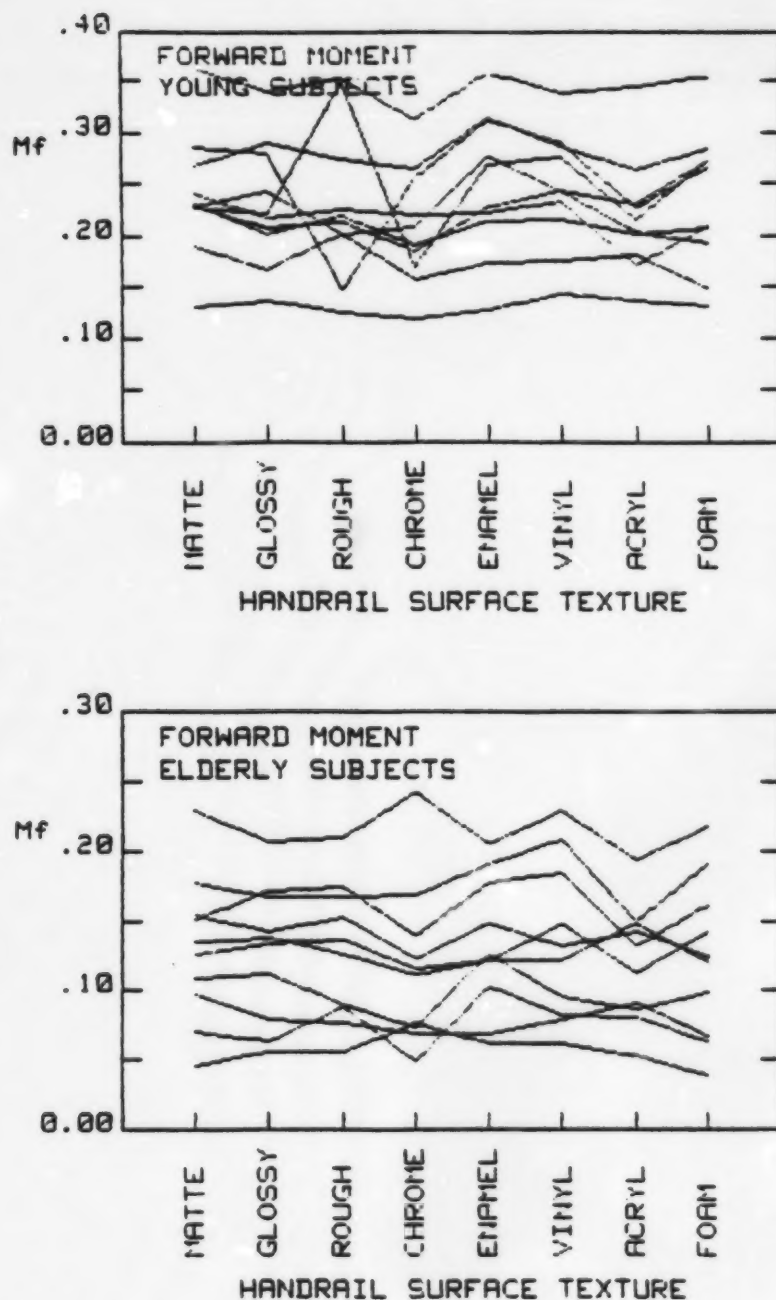


Figure 4.2 Forward Moment versus Handrail Surface - Data

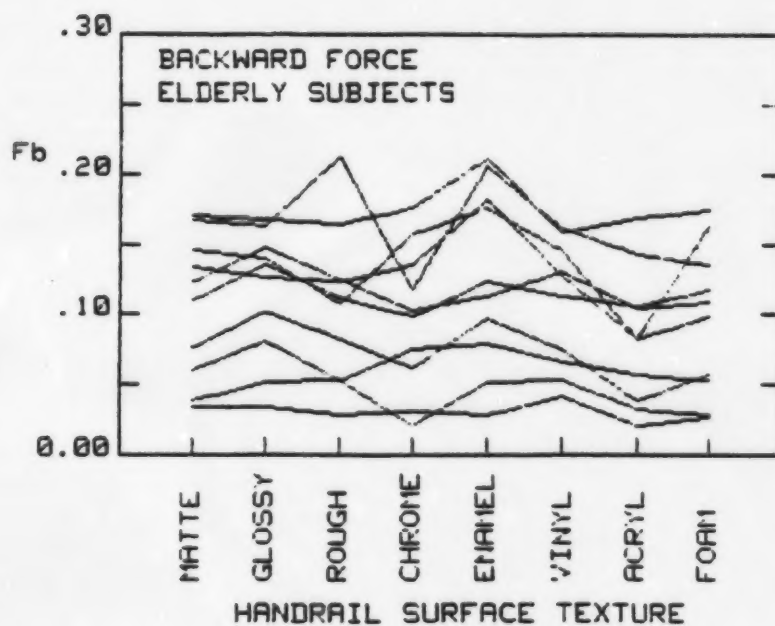
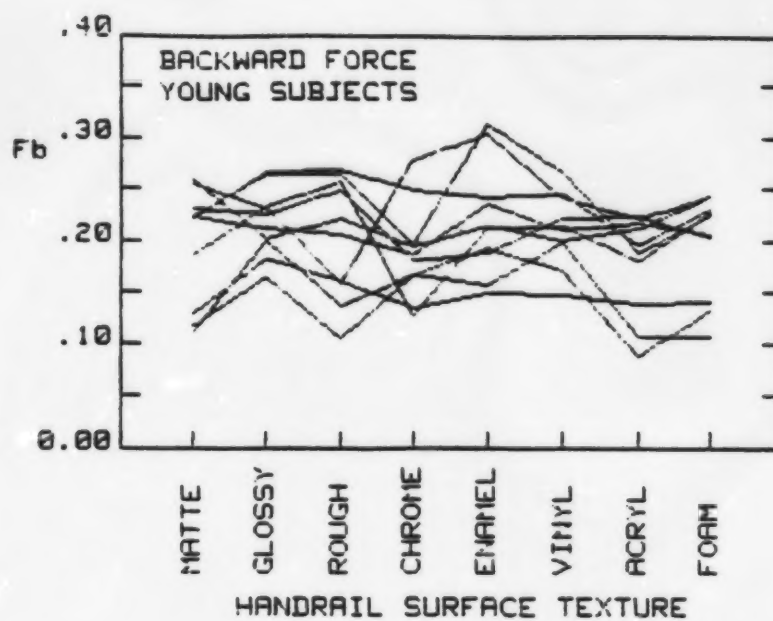


Figure 4.3 Backward Force versus Handrail Surface - Data

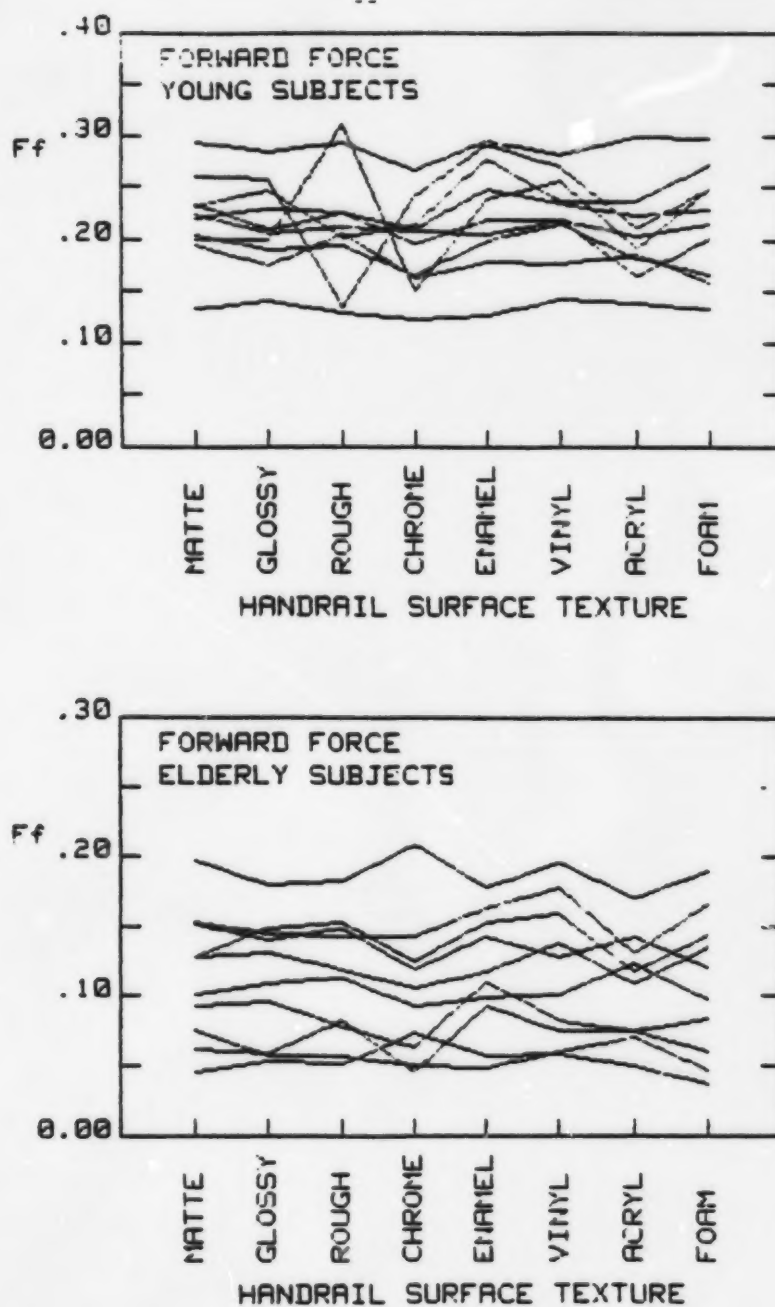


Figure 4.4 Forward Force versus Handrail Surface - Data

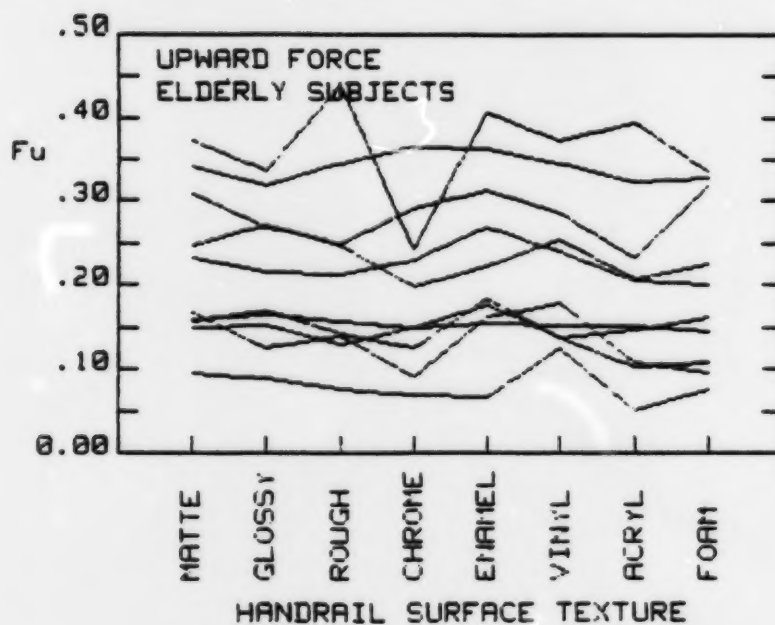
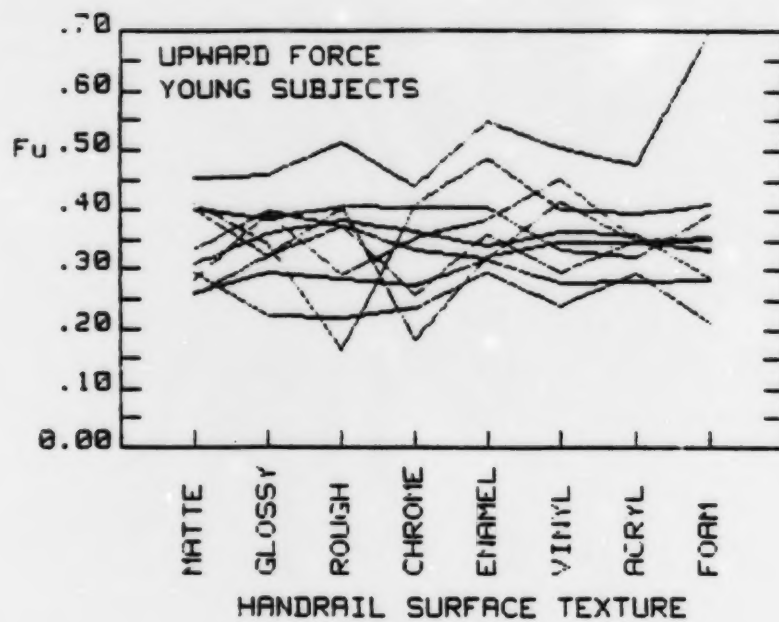


Figure 4.5 Upward Force versus Handrail Surface - Data

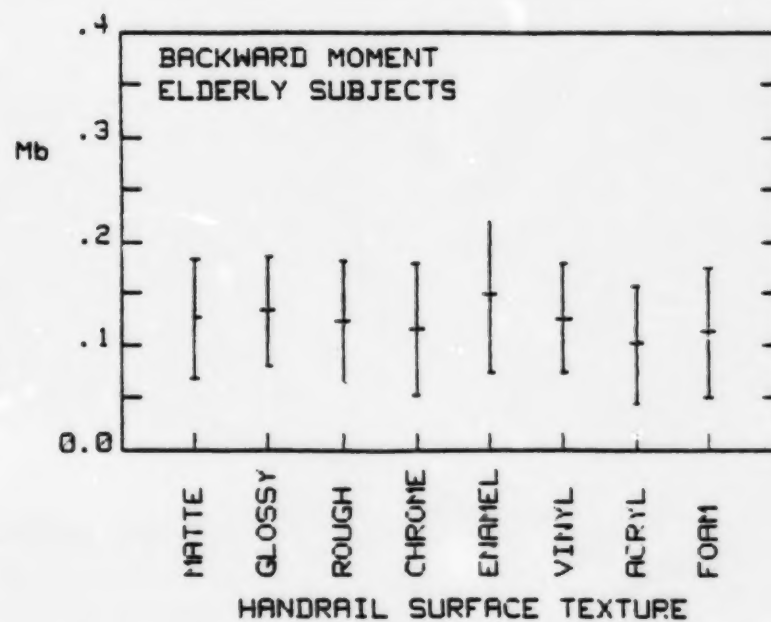
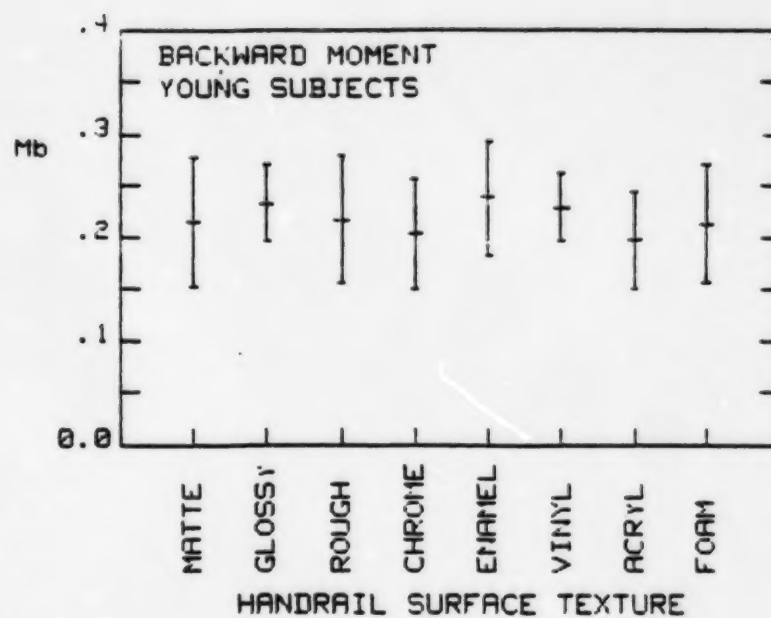


Figure 4.6 Backward Moment versus Handrail Surface - Mean Values

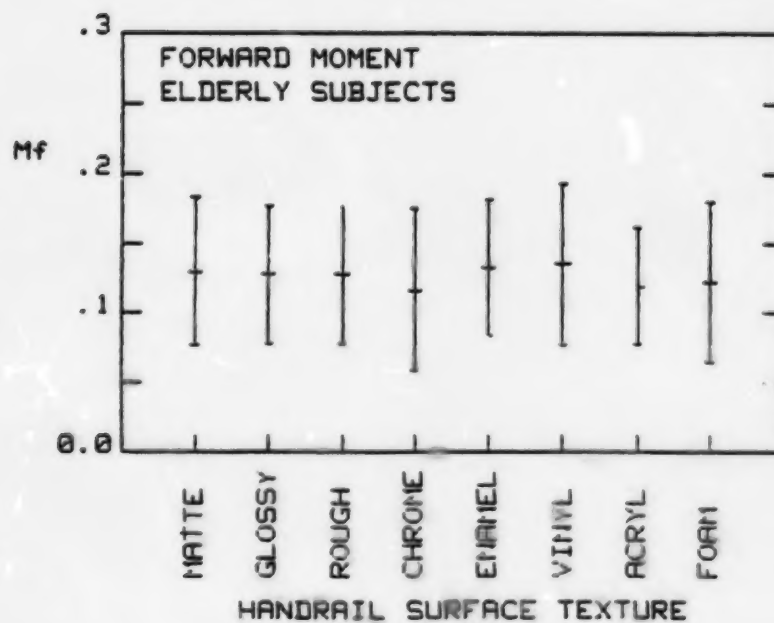
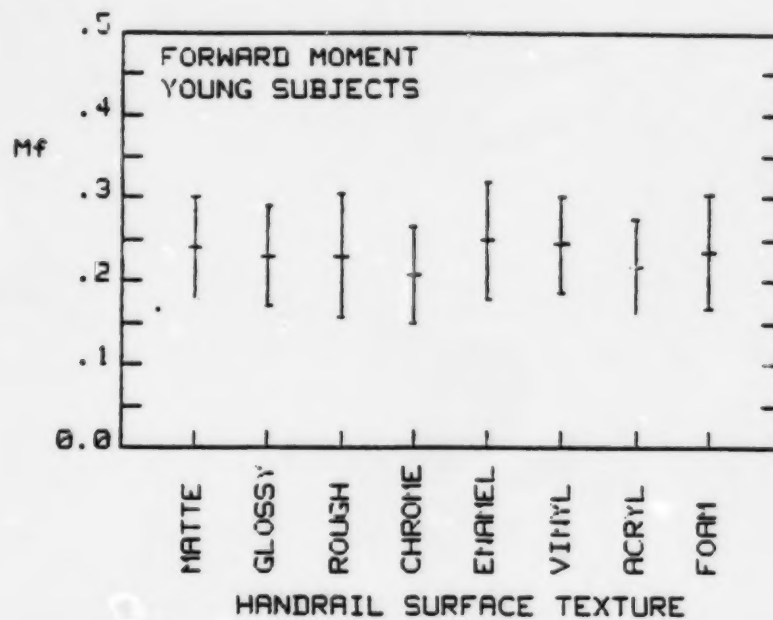


Figure 4.7 Forward Moment versus Handrail Surface - Mean Values

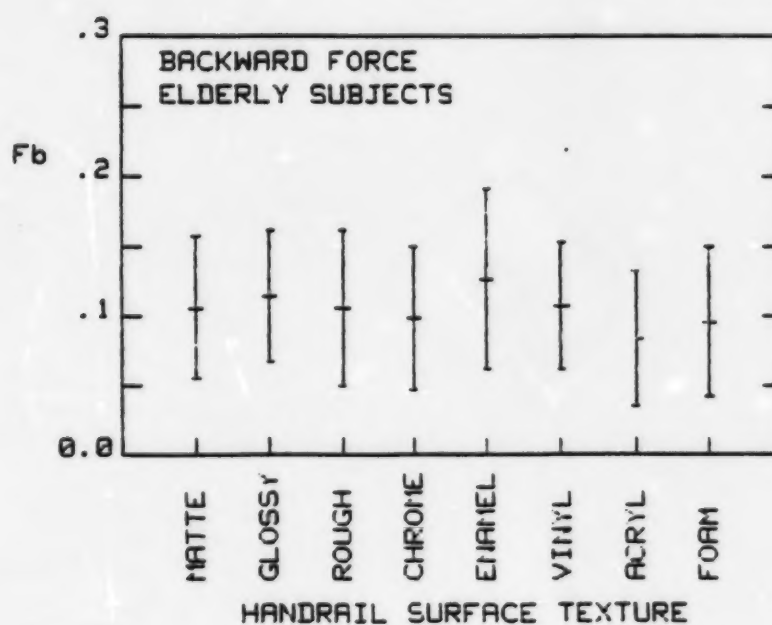
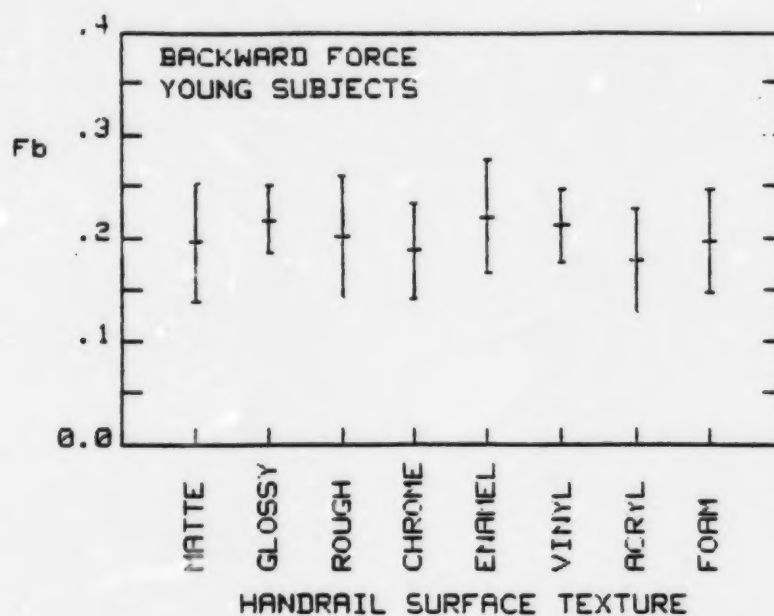


Figure 4.8 Backward Force versus Handrail Surface - Mean Values

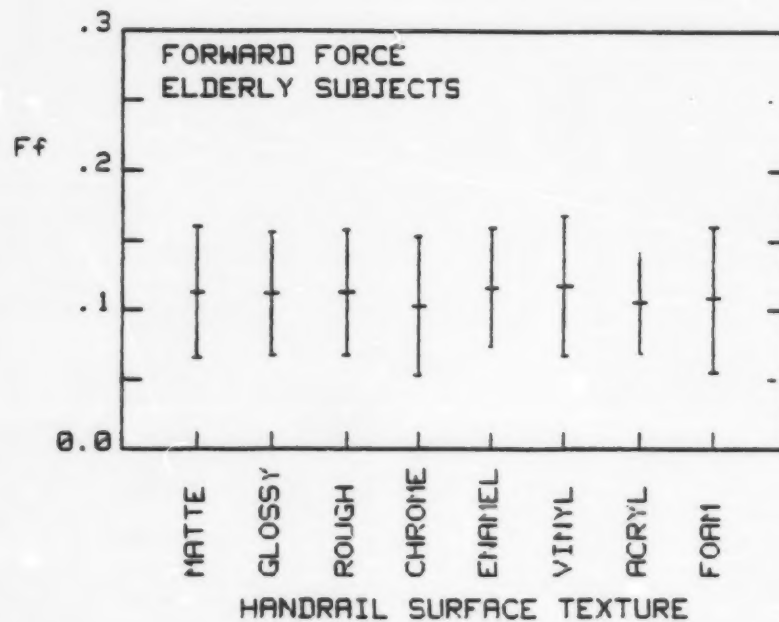
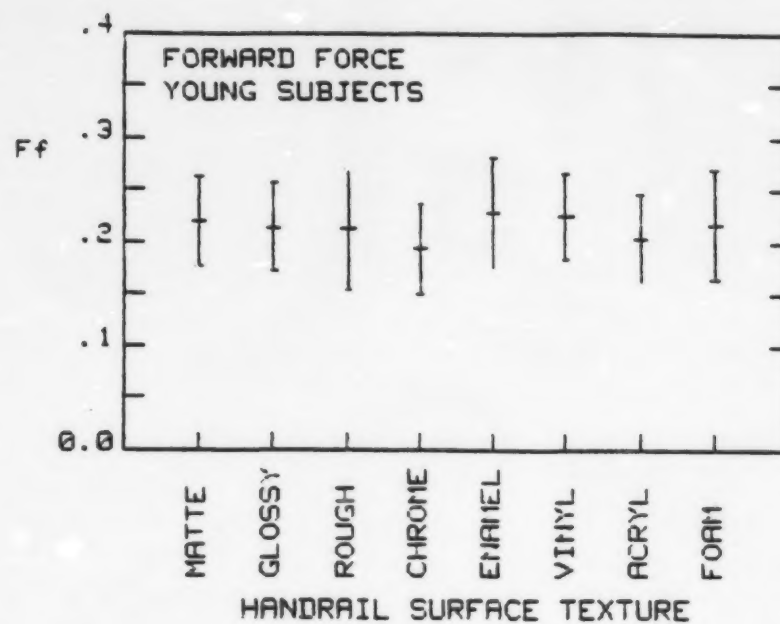


Figure 4.9 Forward Force versus Handrail Surface - Mean Values

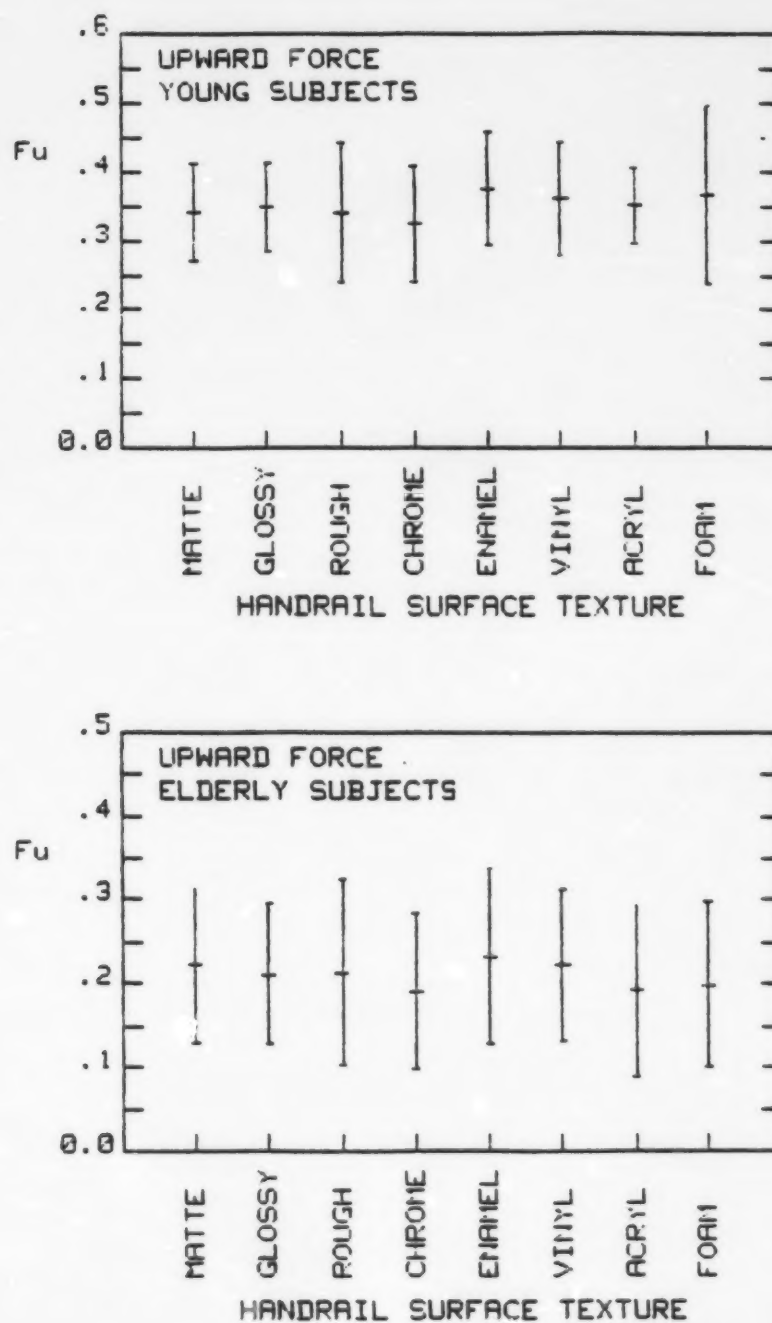


Figure 4.10 Upward Force versus Handrail Surface - Mean Values

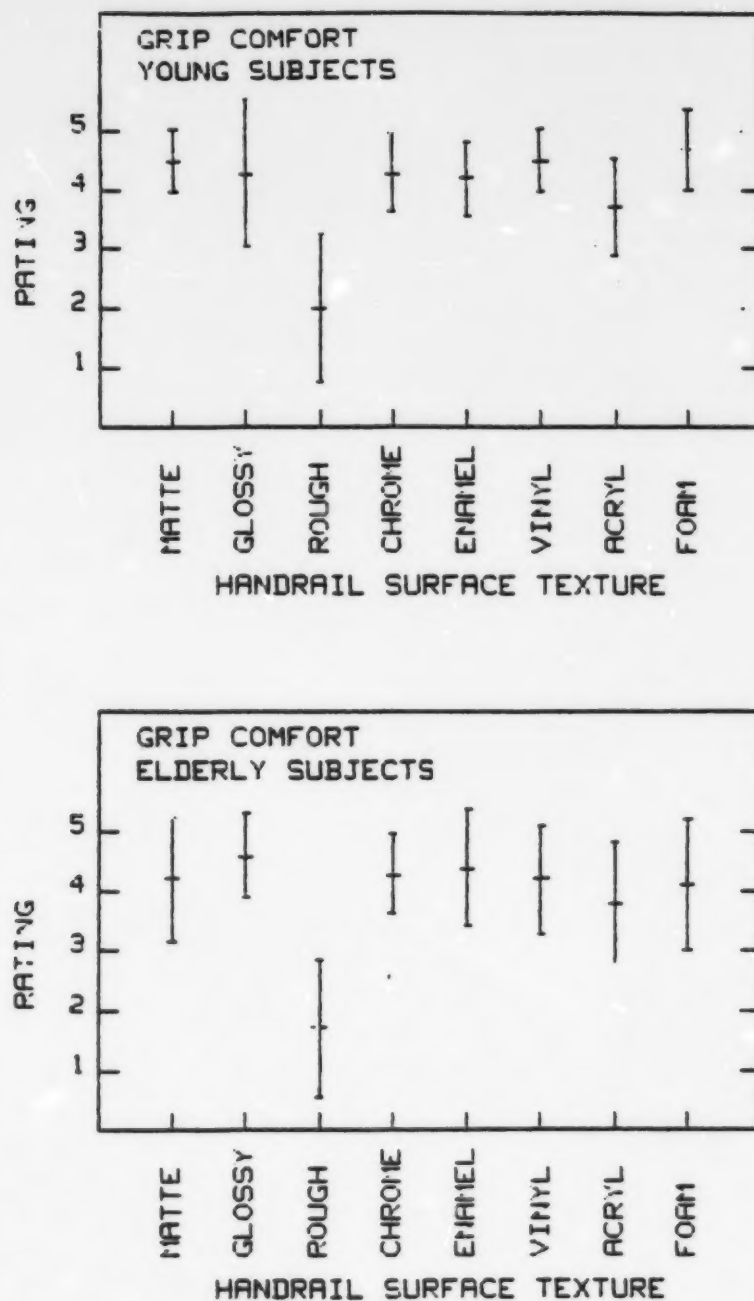


Figure 4.11 Grip Comfort versus Handrail Surface

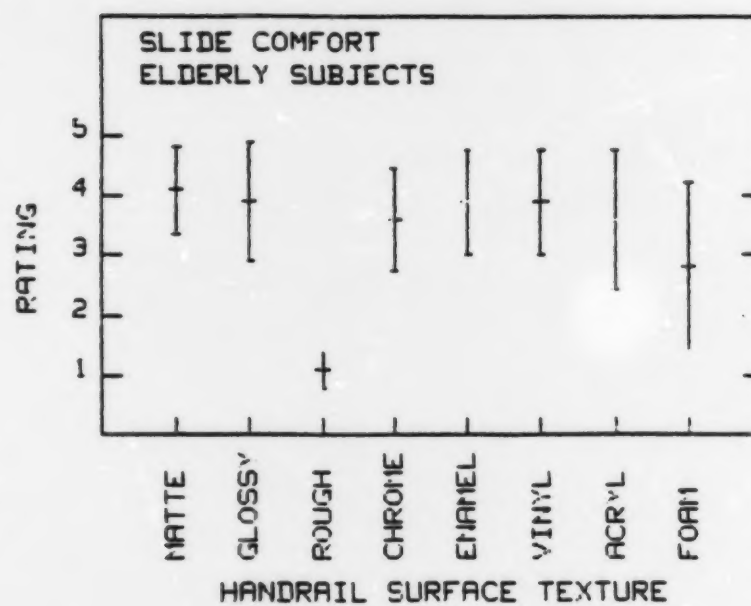
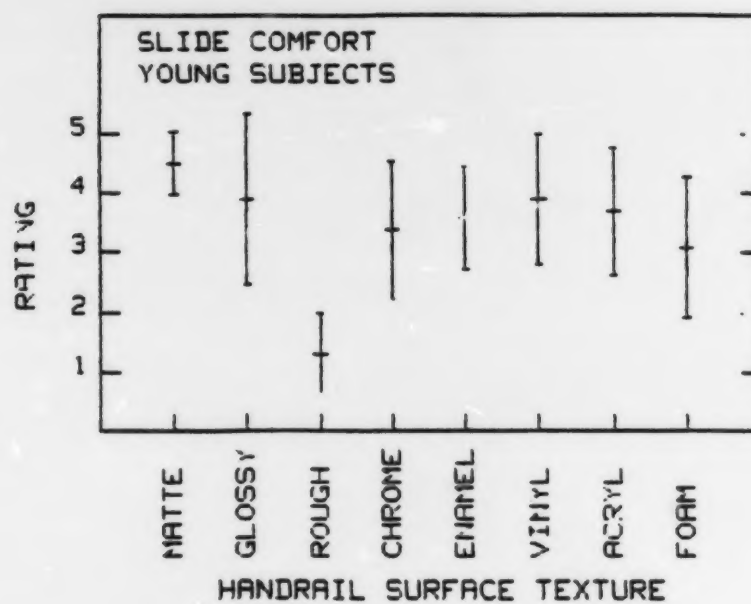


Figure 4.12 Slide Comfort versus Handrail Surface

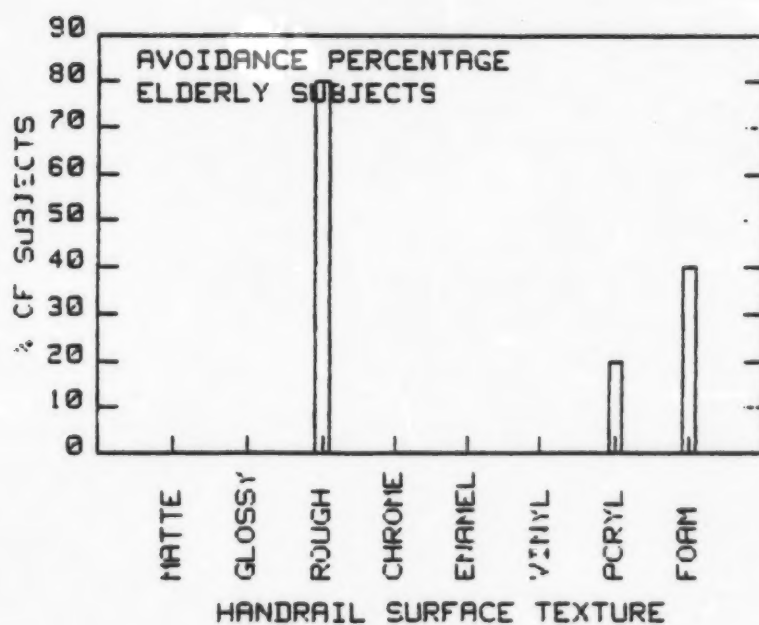
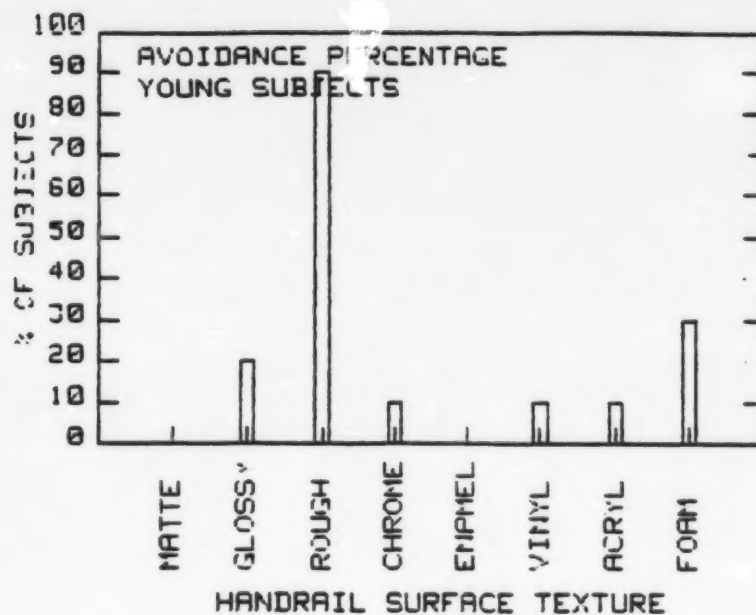


Figure 4.13 Avoidance Percentage versus Handrail Surface

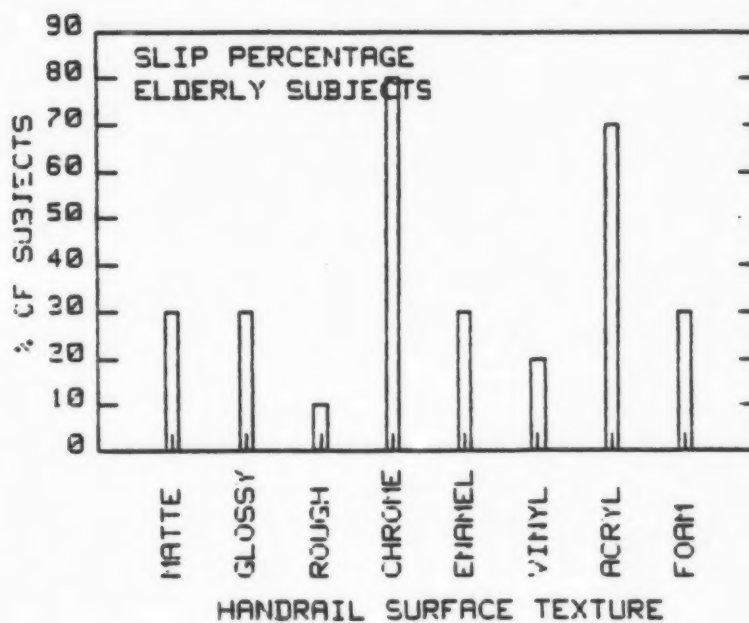
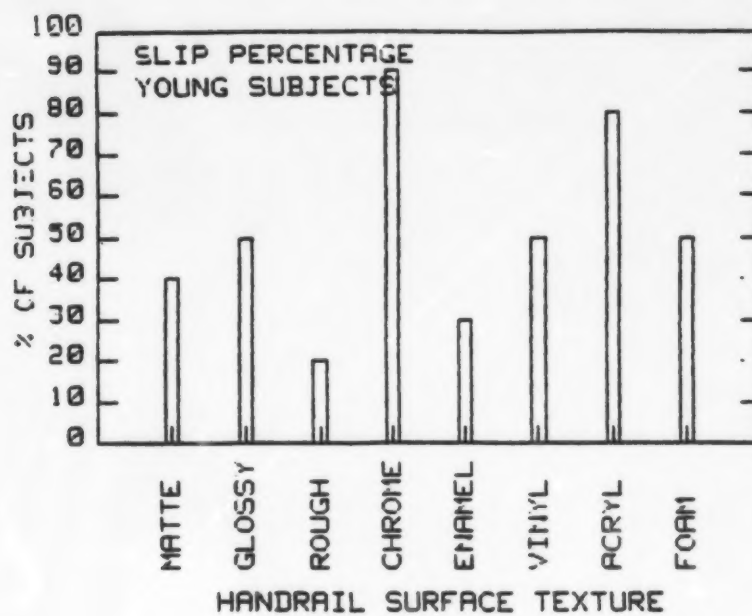


Figure 4.14 Slip Percentage versus Handrail Surface

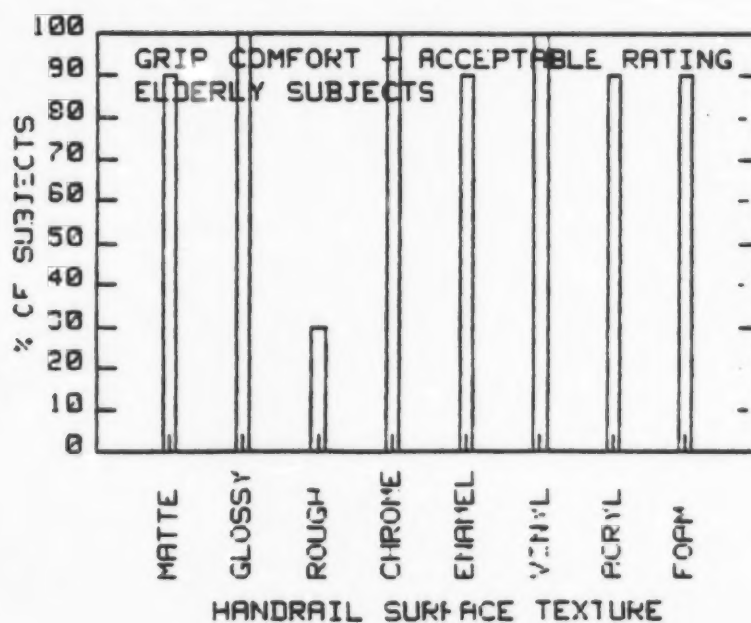
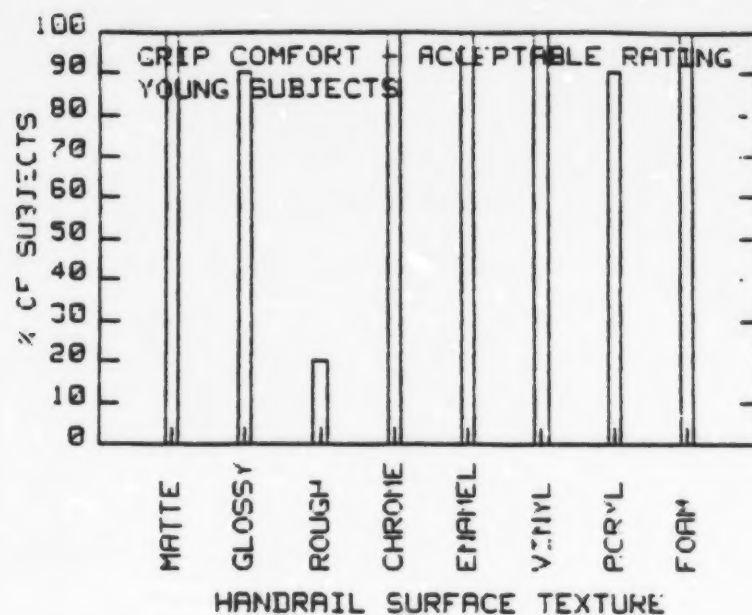


Figure 4.15 Grip Comfort - Percentage with Acceptable Ratings

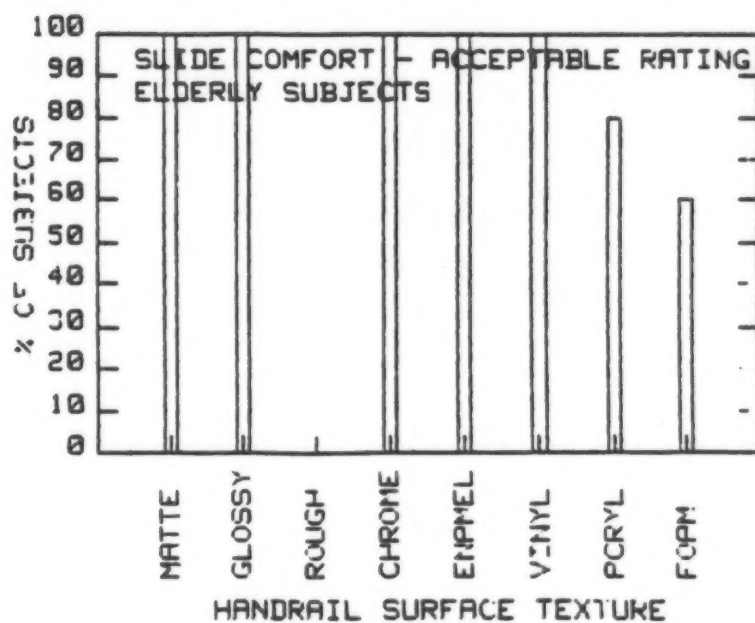
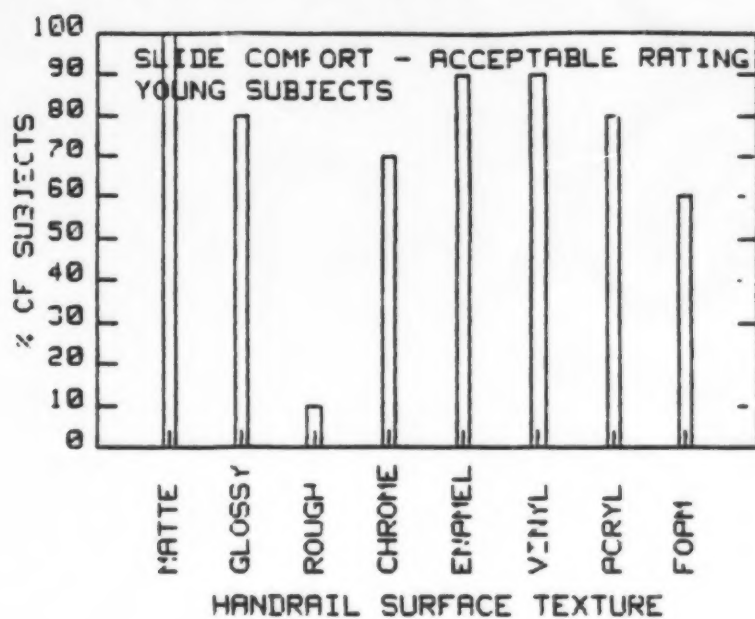


Figure 4.16 Slide Comfort - Percentage with Acceptable Ratings

V DISCUSSION OF RESULTS

5.1 Estimation of the Optimal Design Values

The method by which the optimal design values were calculated does not lend itself to a statistical analysis of significance. Furthermore, in calculating the design range, the definition of "acceptability" was chosen on an operational basis, to allow a reasonably small number of design recommendations to be specified. Therefore, the results should be treated only as estimates of the optimal design values for handrail shape, size and surface texture.

The range of "acceptable" designs can be expanded by relaxing the criterion that the design must be acceptable based on all five forces and moments and on all comfort and avoidance ratings. The criteria for acceptability can also be adjusted. In general, the results for the optimal design values will depend on the definition of optimality, particularly the manner in which the trade-off between force/moment generation and avoidance (due to discomfort) is analyzed.

In view of the somewhat arbitrary nature of the design estimate procedure, it is important to review the recommendations in light of the more rigorous statistical analyses. It should be pointed out that the statistical analysis was based on a comparison of mean values. In contrast, the heuristic design estimation procedure was an attempt to base decisions on the performance of the user population as a whole. To illustrate the differences, consider an individual who generates extraordinarily high forces. The data for this one individual would have a large effect on any statistical comparison of mean values; however, it would have relatively little effect on the design estimation results, since this approach is based only on the requirement that an acceptably large fraction of the population is able to generate acceptably large forces.

For the shape/size data, in cases where statistically significant differences were found, the force/moment analysis indicated that the circular shape and two smallest sizes (100 mm and 120 mm) were the best. The comfort analysis indicated that circular shape was preferred. Thus, the design recommendation of "circular-120 mm" fits in well with the statistical results.

The force/moment analysis of handrail surface texture indicated that the chrome, acrylic-vinyl and foam surfaces were significantly poorer than the other surfaces. The analysis of the comfort ratings showed that the "rough" and foam surfaces were rated significantly lower than the others. Thus, the design recommendation-- glossy, enamel and vinyl--does not conflict with the statistical results.

5.2 Unacceptable Design Values

It is important to analyze the "negative" findings. The force/moment analysis, comfort ratings and design estimate procedures consistently found the "decorative", "rectangular-2x4", and rectangular-"1x6" handrails to be much poorer than the other designs tested. These designs should be avoided.

Regarding the surface textures, the force/moment analysis, comfort ratings and design estimate procedures consistently found the chrome, acrylic-vinyl and foam surfaces to be worse than the others. In addition, the comfort ratings of the "rough" handrail were very poor. The two experimental surfaces, foam and "rough", are not recommended; further development is needed, as discussed in Section 5.3. The chrome surface should also be avoided; however, the recommendation regarding the acrylic-vinyl surface is not so straight-forward.

As pointed out in Section 2.1, the acrylic-vinyl handrail had a flat metal surface on the underside. It is not clear to what extent this factor influenced the force/moment generation. In rating this surface, subjects were instructed to base their ratings on the plastic surface and to ignore the metal undersurface; nonetheless, these ratings may be biased to some extent. An unbiased evaluation of the acrylic-vinyl material is needed. Pending such an evaluation, the results do show that the existing design (i.e. a cylindrical acrylic-vinyl surface with flat metal undersurface) should be avoided.

5.3 Evaluation of the Experimental Surface Textures

The foam surface was an attempt to develop a handrail with a compliant surface, to allow a comfortable yet strong grip for individuals with decreased grip strength and finger flexibility (e.g. the elderly). The grip comfort ratings for this surface were, in fact, very high; however, the sliding comfort ratings were low, due primarily to the frictional heat generated. Conceivably, the problems with sliding friction (and hygiene) could be overcome by covering the foam with a thin plastic sleeve. However, even if the frictional heat problem is overcome, the problem remains that the force/moment generation for this surface was poor. The poor performance is probably due to shearing of the compliant material. This problem could be remedied to some extent by using a higher-density foam and by reducing the thickness of the foam layer. Clearly, more development work is needed; however, the initial indications from the results of this study are not promising. The concept of a compliant surface handrail may in fact have only very limited application for populations with severe hand disabilities.

The "rough" surface texture was an attempt to reduce slippage of the hand by increasing the shear strength of the hand-handrail interface. The effect is much greater than a simple increase in adhesive friction, as the asperities in the handrail surface tend to "interlock" with the soft tissue of the hand on a macroscopic scale. Apparently, the design was

effective in reducing slippage, as evidenced by the very low slippage incidence reported by the subjects. However, in spite of the low slippage, there was no significant improvement in force/moment generation relative to the other surfaces tested. Moreover, the rough surface resulted in very poor comfort ratings and a very high avoidance percentage. Because of these problems, this particular design is unacceptable. It is possible that an acceptable design could be achieved by reducing the size of the asperities; however, more development work is needed. It should also be noted that this type of design does present a considerable cleaning and hygiene problem.

5.4 Biomechanics

The biomechanics of gripping a handrail were discussed in detail in the first report [Maki and Fernie, 1983]. The most important points of that discussion can be summarized as follows:

- (1) large stabilizing forces and moments can be generated if the tangential and normal components of the grip force are maximized;
- (2) the tangential component of the grip force is dependent on the friction between the hand and handrail; this friction is dependent on the roughness of the surfaces (hand and handrail) and on the magnitude of the effective normal force (i.e. the sum of the normal forces acting on each segment of the hand);
- (3) the magnitude of the normal component of the grip force and the magnitude of the effective normal force (and hence the tangential force) are maximized by a "power" grip, that is, a grip where all phalangeal and metatarsophalangeal joints are in a flexed position, with all segments of the hand contacting the handrail;
- (4) in order to generate substantial "pulling" forces, the fingers and thumb must be able to "wrap around" the undersurface of the handrail; this will not be possible if the handrail is too large;
- (5) if the handrail is too small, then "interference" between fingertips, thumb and the palm may prevent achievement of a strong power grip;
- (6) the surfaces of the handrail should have large radii-of-curvature so as to distribute the grip forces over a large area, thereby minimizing discomfort, pain, compression of arteries and nerves, and the possible limitation of grip strength due to these factors;
- (7) in selecting the optimal handrail shape and size for generating grip force, the above criteria must be satisfied for the large range of hand sizes existing in the general stairway user population; the circular shape is most likely to accomplish this objective because a circular shape of sufficient diameter will always allow all hand, finger and thumb segments to contact the handrail in a flexed position; other shapes may be optimal for certain hand sizes, but are unlikely to allow a power grip for a wide range of hand sizes and shapes.

The experimental results confirm many of the above principles. Overall, the circular shape was found to result in better force/moment generation than the square or rectangular shapes. As illustrated in Figure 5.1, the narrow rectangular shapes (narrow on top) required the use

of a pinch grip, rather than a power grip, and did not allow the user to grip the undersurface of the handrail. As a result, force and moment generation with this type of handrail was very poor.

The oval shape was comparable to the circular shape in force/moment generation, as well as comfort. Since this shape was studied in only one size, it is possible that other sizes of oval shapes may in fact produce even better results. However, the oval shape does have the disadvantage that it is relatively difficult to fabricate.

As illustrated in Figure 5.2, some of the larger sizes prevented subjects with small hands from attaining an adequate purchase on the undersurface of the handrail. Accordingly, force and moment generation was often poorer for the larger sizes.

As illustrated in Figure 5.3, some of the smaller sizes created interference problems for subjects with large hands. However, the results showed that the smaller sizes were actually the best for force/moment generation. Apparently, the amount of interference was not so large as to significantly decrease gripping force.

The importance of the frictional characteristics of the handrail were evidenced by the differences in force/moment generation achieved using the different surface textures. In addition, the subjective reports of slipping appear to correlate with poor force/moment generation.

5.5 Interaction between Handrail Shape and Size

Armstrong (1978) attempted to derive specifications for optimal handrail shape and size independent of each other. The results of the present study demonstrate that this is not always possible. In several instances (e.g. backward moment for the young subjects, comfort ratings for the elderly subjects), the statistical analysis found significant interaction between handrail shape and size.

5.6 Limitations of the Present Study

The conclusions of the present study are limited to the range of shapes, sizes and textures actually tested. Generalization of the results is also limited by the small number of subjects tested and by the assumptions of the static force/moment measurements. In addition, the hardware used to mount the handrail may influence the graspability of a given handrail design.

5.6.1 Mounting Arrangements

The present work has not assessed the influence of the mounting arrangements for the handrail. In practice, the supporting posts or brackets may interfere with gripping the handrail. In designs involving small handrails and closely-spaced vertical posts, the grip may actually encompass a portion of the supporting posts as well as the handrail

itself. In stairway ascent, the opportunity to wrap the fingers around the posts could conceivably aid in achieving a strong grip. In descent, however, the posts cannot be gripped easily and interference with the handrail grip will likely become a problem.

The potential problems created by the mounting hardware are dependent on the size of the handrail, and possibly the shape as well. For larger handrails, the mounting arrangements may be less critical, for two reasons. First, the mounting hardware is less likely to interfere with the grip, as a result of the limited "wrap-around" that occurs (particularly for users with small hands). Secondly, a smaller number of mounting fixtures can be used, since spacing between mounting fixtures can be increased as a result of the greater rigidity of the handrail.

There is a trade-off: smaller handrail sizes may enhance gripping ability whereas larger handrail sizes may reduce interference between the grip and the mounting hardware. This issue requires further investigation; however, one general recommendation is obvious: the spacing between handrail supports should be maximized (to the extent that the structural strength and rigidity are not compromised).

In some cases, it may be possible to reduce the interference problems through intelligent placement of the mounting fixtures. For the smaller handrail sizes (e.g. 100-mm and 120-mm), it seems unavoidable that interference will occur, regardless of the post locations. However, for the larger sizes (e.g. 140-mm and 160-mm), it may be possible to reduce interference with finger placement during stairway descent by shifting the attachment points (on the underside of the handrail) towards the stairwell. Horizontal posts on the wall side will seriously impair finger placement (in stairway descent) and should be avoided.

5.6.2 Statistical Considerations

In a study involving gripping action, hand size is obviously an important variable. This observation is supported by the results of the previous study (Maki, 1984) in which hand size was found to be the dominant anthropometric characteristic in determining handrail force/moment generating ability. Ideally, the experiments would be performed with a large number of subjects selected at random and this large sample would likely include a wide range of hand sizes. However, because of the limited time and funding available, only a small number of subjects were used in the present study. In order to ensure that this small sample included a range of hand sizes representative of the general stairway user population, the subjects were selected to represent specific ranges of hand size, for each sex.

In order to study the influence of hand size, a number of subjects would be selected at random to represent each category of hand size (for each sex and age group), and hand size, sex and age group would be included as experimental factors. In the present study, only one subject (for each sex and age group) was tested for each category of hand size. As a result, variation due to hand size cannot be separated from the variation due to other subject characteristics, hand size cannot be

included as a factor in the analysis, and no conclusions can be drawn as to the influence of this variable. To account for the variability in the data due to differences in hand size and other subject characteristics, the subjects were considered as blocks.

Because of the limitations of the available statistical software, a continuous normal variable ANOVA model was used to study the comfort ratings. This is a crude approximation; however, the errors introduced by this approximation are not likely to affect the conclusions drawn, considering the large differences that were found to occur in the mean comfort ratings.

5.6.3 Limitations of the Static Measurements

The assumptions underlying the static force/moment measurements should be emphasized. The erect posture is a reasonable approximation of body position at the beginning of a fall; therefore, the static force measurements made in this position should give an indication of the maximum stabilizing forces and moments that could be generated at the start of a fall. Measurement of maximal values provides a suitable basis for comparing different handrail designs; however, there is no implication that these levels of force and moment would actually be generated during a fall. Other factors (e.g. time delay in the individual's response) may prevent the subject from attaining his/her maximal capabilities. Furthermore, as the body proceeds to fall forward, the actual forces and moments that can be exerted will change due to positional changes of the body relative to the handrail. In addition, muscle force generation will change under dynamic conditions.

Although the stabilizing force and moment exerted during an actual fall may vary considerably due to the dynamic and positional effects discussed above, increased capability for generating stabilizing forces and moments during the initial stages of a fall would be expected to correlate with an increased probability of balance recovery. Therefore, static measurements made in an erect position should provide a useful basis for specification of optimal handrail design.

Use of dynamic testing to verify our static results would be valuable, but is beyond the scope of the present work. Such experiments could involve applying postural perturbations to subjects and observing their ability to prevent loss of balance, using handrails of different design. Because of safety concerns, any studies involving actual loss of balance would have to preclude elderly subjects; however, there is no reason why healthy, young volunteers could not be studied, provided that appropriate safety measures are taken (e.g. padding of surfaces, wearing of safety harnesses, etc).

The results of the present study represent the first direct experimental evidence regarding the influence of handrail shape, size and surface texture on stairway safety, and are therefore recommended for use as a basis for selection of handrail design, at least until such time as dynamic perturbation studies can be carried out to verify the relevance of the static measurements.

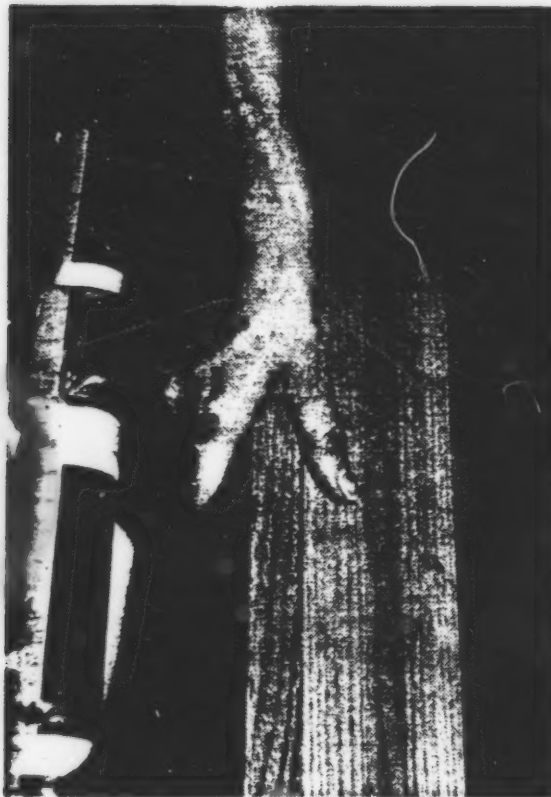


Figure 5.1 - The Pinch Grip



Figure 5.2 - Inadequate "Wrap-Around"

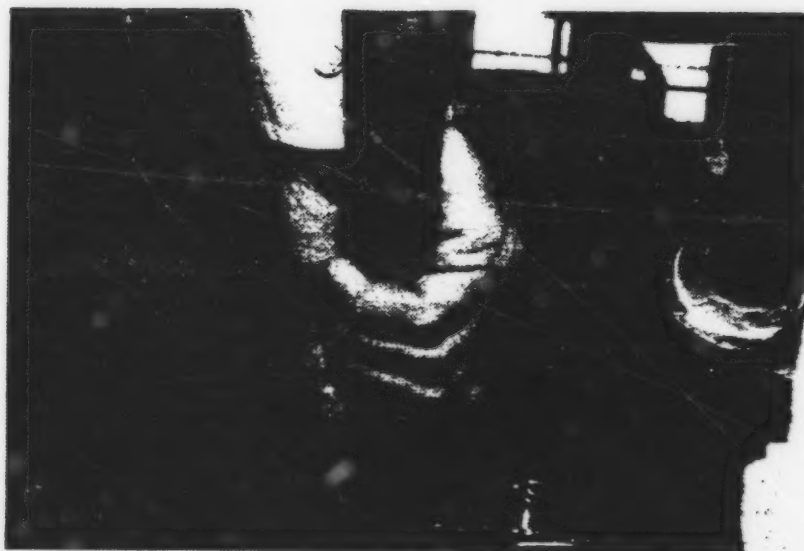


Figure 5.3 - Finger "Interference"

VI CONCLUSIONS

(1) Handrail shape, size and surface texture had a significant influence on the ability to generate certain stabilizing forces and moments. The particular forces and moments that were affected depended on the age group.

(i) of the three "basic" shapes tested, the largest stabilizing forces and moments were generated using a circular handrail (for the young subjects);

(ii) of the four circumference sizes tested, the smallest stabilizing forces and moments were generated using the 140-mm size (for the young subjects) and the 160-mm size (for the elderly subjects);

(iii) there was significant interaction between handrail shape and size in generating backward moment (for the young subjects);

(iv) of all the shapes tested, the smallest stabilizing forces and moments were generated using the "narrow-top" rectangular shapes and the "decorative" shape;

(v) of all the surfaces tested, the smallest stabilizing forces and moments were generated using the chrome and acrylic-vinyl surfaces (for both age groups) and foam surface (for the elderly subjects).

(2) Handrail shape, size and surface texture had a significant influence on user ratings of grip comfort and sliding comfort.

(i) of the three "basic" shapes tested, the circular shape was preferred (by the young subjects);

(ii) for the elderly subjects, there was significant interaction between handrail shape and size;

(iii) of all the designs tested, the circular (all sizes) and oval handrails generally had the highest comfort ratings;

(iv) of all the designs tested, the "narrow-top" rectangular and "decorative" handrails were generally rated lowest;

(v) of the surfaces tested, the "rough" surface was rated lowest in terms of grip and sliding comfort; the foam surface was also rated lowest for sliding comfort (by the young subjects).

(3) The recommended design values are as follows:

(i) circular handrail with circumference of 120 mm (diameter of 38 mm or 1-1/2 inches)

(ii) surface of glossy varnish (on hardwood), enamel paint (on metal), or vinyl.

(4) The following design values should be avoided:

(i) "narrow-top" rectangular and "decorative" shapes;

(ii) chrome-plated, "rough" (sand-in-paint on hardwood) and polyurethane-foam surfaces.

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APPENDIX A - DETAILS OF THE SURFACE PREPARATIONS

1. "matte" surface:

- matte varnish ("Varathane Satin Finish") on sanded birch
- 2 coats

2. "glossy" surface:

- glossy varnish ("Varathane Gloss Finish") on sanded birch
- 2 coats

3. "rough" surface:

- mixture of coarse sand in oil-base paint ("St Clair Semi-Gloss Silk")
- 1-kg sand per liter of paint
- 1 coat

4. "chrome" surface

- commercial handrail supplied by ITT Fluid Products Canada (Guelph, Ontario)
- chrome-plated steel tubing (44 mm outer diameter)

5. "enamel" surface:

- enamel paint ("Tremclad Rust Paint") on steel pipe (44 mm outer diameter)
- 2 coats

6. "vinyl" surface:

- vinyl tubing supplied by Alku Plastics, Ltd., (Downsview, Ontario)
- tubing heated in boiling water, placed over Aluminum tubing (35 mm outer diameter) and glued with cyanoacrylate ("Super Glue")

7. "acrylic-vinyl" surface:

- commercial handrail ("Acrovyn", Model H6)
- supplied by Construction Specialties, Ltd. (Mississauga, Ontario)

8. "foam" surface:

- low-density polyurethane foam (6mm thick)
- glued with cyanoacrylate ("Super Glue") to Aluminum tubing (32 mm outer diameter)